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Retrievals of ice microphysics using dual-wavelength polarimetric radar observations during stratiform precipitation events

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Abstract. Ice growth processes within clouds affect the type as well as the amount of precipitation. Hence, the importance of an accurate representation of ice microphysics in numerical weather and numerical climate models has been confirmed by several studies. To better constrain ice processes in models, we need to study ice cloud regions before and during monitored
10 precipitation events. For this purpose, two radar instruments facing each other were used to collect complementary measurements. The C-band POLDIRAD weather radar from the German Aerospace Center (DLR), Oberpfaffenhofen and the Ka-band MIRA-35 cloud radar from the Ludwig Maximilians University of Munich (LMU) were used to monitor stratiform precipitation in the vertical cross-section area between both instruments. The logarithmic difference of radar reflectivities at two different wavelengths (54.5 and 8.5 mm), known as dual-wavelength ratio, was exploited to provide information about
15 the size of the detected ice hydrometeors, taking advantage of the different scattering behavior in the Rayleigh and Mie regime. Along with the dual-wavelength ratio, differential radar reflectivity measurements from POLDIRAD provided information about the apparent shape of the detected ice hydrometeors. Scattering simulations using the T-matrix method were performed for oblate and horizontally aligned prolate ice spheroids of varying shape and size using a realistic particle size distribution and a well-established mass-size relationship. The combination of dual-wavelength ratio, radar reflectivity and differential
20 radar reflectivity measurements as well as scattering simulations was used for the development of a novel retrieval for ice cloud microphysics. The development of the retrieval scheme also comprised a method to estimate the hydrometeor attenuation in both radar bands. To demonstrate this approach, a feasibility study was conducted on three stratiform snow events which were monitored over Munich in January 2019. The ice retrieval can obtain ice particle shape, size and mass which are in line with differential radar reflectivity, dual-wavelength ratio and radar reflectivity observations when a suitable mass-size relation
25 is used and when ice hydrometeors are assumed to be represented by oblate ice spheroids. A furthermore finding was the importance of the differential radar reflectivity for the particle size retrieval directly above the MIRA-35 cloud radar. Especially for that observation geometry, the simultaneous slantwise observation from the polarimetric weather radar POLDIRAD could reduce ambiguities in retrieval of the ice particle size by constraining the ice particle shape.

1 Introduction

30 The ice phase is the predominant cloud phase at mid and higher latitudes (Field and Heymsfield, 2015). Ice clouds can cause a cooling effect at the surface by reflecting the shortwave, incoming solar radiation but they can also contribute to warming of the atmosphere by trapping the longwave, terrestrial radiation (Liou, 1986). Their influence on the radiation budget of the climate system strongly depends on their top height as well as on ice crystals habits and effective ice crystal size (Zhang et al., 2002). Ice growth processes, such as deposition, riming and aggregation, play a leading role in the formation of
35 precipitation and are a central topic in many ice cloud studies. A misrepresentation of these processes in numerical weather models can lead to high uncertainties and therefore, they need to be constrained as accurately as possible. Brdar and Seifert (2018) presented the novel Monte-Carlo microphysical model, McSnow, aiming for a better representation of aggregation and riming processes of ice particles. When numerical weather models are used to predict microphysics information about ice hydrometeors (e.g. Predicted Particle Properties (P3), Part I, Morrison and Milbrandt, 2015), we need to investigate under

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40 which conditions each ice growth process occurs. To better understand these mechanisms and improve their representation in
models, more precise microphysics information (e.g. size, shape and mass) through ice retrievals based on measurements, is
needed.

Many studies showed how millimeter-wave radar measurements can be used to retrieve ice water content (IWC) profiles
in clouds (e.g. Hogan et al., 2006). However, stand-alone single-frequency radar measurements cannot constrain microphysical

45 properties such as ice particle size and shape simultaneously without using empirical relations. Dealing with more parameters
(e.g., IWC, size and shape) more measurements are needed. Thus, observations or simulated radar parameters are often
combined with other remote sensing instruments, e.g. with lidars, to retrieve microphysics properties such as the effective
radius of cloud ice particles (Cazenave et al., 2019), or with infrared radiometers (Matrosov et al., 1994) to retrieve the median
diameter of the ice particles size distribution. Another way to gain microphysics information is to use multi-frequency radar

50 observations as they exploit the scattering properties of ice particles in both Rayleigh and Mie regime. To this end, frequencies
are chosen with respect to the prevalent ice particle size. In the case of dual-frequency techniques, one frequency is chosen to
be in the Rayleigh regime (e.g. S-, C- or X-band), where particle size is much smaller than the radar wavelength, and the other
is chosen to be in the Mie regime (e.g. Ka-, Ku- or W-band), where particle size is comparable or larger than the radar
wavelength. The scattering of radar waves is sensitive to the size and number concentration of particles. The radar reflectivity

55 factor z is defined as the sixth moment of the particle size distribution $N(D)$ and is thus designed to be proportional to the to
the Rayleigh scattering cross section of liquid spheres:

$$z \: [mm^6 \: m^{-3}] = \int_0^\infty N(D)D^6 dD \tag{1a}$$

where,

z: the radar reflectivity in linear scale,

60 N: the number concentration,

D: the geometric diameter of the particles.

This definition can be also expressed in logarithmic terms:

$$Z \: [dBZ] = 10 \cdot log_{10}(z). \tag{1b}$$

This definition, however, cannot be directly applied to snow due to the varying density, the irregular shape and larger size of

65 ice particles which cause deviations from the Rayleigh into the Mie scattering regime. Nevertheless, an equivalent radar
reflectivity factor Z_e can be derived from the measured radar reflectivity η when the dielectric factor of water $|K|^2 = 0.93$ is
assumed:

$$z_e[mm^6 m^{-3}] = \frac{\lambda^4}{\pi^5 |K|^2} \cdot \eta \text{ and } Z_e[dBZ] = 10 \cdot log_{10}(z_e) \tag{1c}$$

where:

70 λ: the radar wavelength. In the Rayleigh regime, the radar reflectivity factor Z or the equivalent radar reflectivity factor Z_e (for
simplicity reasons referred also as radar reflectivity in this paper) is proportional to the sixth power of the particle size, while
in the Mie regime Z_e scales with the second power of the particle size. In both regimes Z_e scales linearly with the particle
number concentration. The logarithmic difference of these radar reflectivities in Eq. (2), known as dual-wavelength ratio
(DWR), is a parameter that can be used to infer the size of the observed hydrometeors in the atmosphere as it increases with

75 the particles size:

$$DWR_{\lambda1,\lambda2} \: [dB] = 10 \cdot log_{10}\left(\frac{z_{e,\lambda1}}{z_{e,\lambda2}}\right) \text{ or } DWR_{\lambda1,\lambda2}[dB] = Z_{e,\lambda1}[dBZ] - Z_{e,\lambda2}[dBZ], \tag{2}$$

with $\lambda_1 > \lambda_2$ the radar wavelengths, $z_{e,\lambda1}$, $z_{e,\lambda2}$ the radar reflectivities of the two radar bands in linear scale (units: $mm^6 \: m^{-3}$) and
$Z_{e,\lambda1}$, $Z_{e,\lambda2}$ the radar reflectivities of the two radar bands in logarithmic scale (units: dBZ). The DWR method has been used in

many ice studies before. Matrosov (1998) developed a DWR method to estimate the snowfall rate R, supplementing

80   experimental Z_e-R relations with a retrieved median size, while in Huang et al. (2019) the DWR was used for Quantitative
Precipitation Estimation (QPE) from the combination of Ku- and Ka-band which were accounted to be Rayleigh and Mie
region, respectively, for the detected particles sizes. In other studies, such as Hogan and Illingworth (1999) and Hogan et al.
(2000), DWR from airborne and ground-based radars was used to estimate ice crystals sizes as well as IWC for cirrus clouds.
Sometimes two DWR measurements are combined to exploit the information in triple-frequency radar measurements. Kneifel

85   et al. (2015) used the triple-frequency method ($DWR_{X, Ka}$ and $DWR_{Ka, w}$) to derive ice particle habits information from three
snowfall events measured during the Biogenic Aerosols Effects on Clouds and Climate (BAECC) field campaign (Petäjä et
al., 2016). The triple-frequency method was also used by Leinonen et al. (2018b) to develop an algorithm that retrieves ice
particle size and density as well as number concentration using airborne radar data from the Olympic Mountains Experiment
(OLYMPEX, Houze et al., 2017).

90   Beyond DWR techniques, polarimetric radar measurements are used in many snowfall rate estimation studies. E.g.
Bukovčić et al. (2018) used polarimetry to study the snow water equivalent rate and IWC. Except for such studies, polarimetry
is an advantageous tool to obtain information about ice particles, e.g. their size distribution and their shape. Additional
characteristics, like the orientation and canting angle distribution, as well as the variable refractive index of melting or rimed
ice crystals have specific polarimetric radar signatures. Polarimetric weather radars can provide observational parameters

95   including Z_e, differential radar reflectivity (ZDR), linear depolarization ratio (LDR), reflectivity difference (ZDP), cross-
correlation coefficient (ρHV), differential propagation phase (φDP) and specific propagation phase (KDP). These parameters
have been widely used in classification schemes of atmospheric hydrometeors. Höller et al. (1994) developed one of the first
algorithms to distinguish between rain, hail, single or multi-cells. Subsequently, this algorithm was extended to estimate
hydrometeor mass concentrations (Höller, 1995). Straka et al. (2000) developed a method to distinguish hydrometeor types

100   using radar observations and model calculations at a wavelength of 10 cm. Other studies suggested to use polarimetry to
investigate growth processes of snow and their signatures on dual-polarization and Doppler velocity radar observations
(Moisseev et al., 2015). Tiira and Moisseev (2020) developed an unsupervised classification of snow and ice crystals particles
exploiting profiles of polarimetric signatures on radar variables. The most important growth processes of ice particles were
studied using several years of the Ikaalinen C-band radar data, in Hyytiälä forestry station in Juupajoki, Finland.

105   Scattering simulations as well as polarimetric radar simulations can be used to extract additional information regarding
the microphysical properties of the observed hydrometeors. However, in the case of ice particles this can be challenging due
to the large complexity and variety in shape, structure, size and density of ice crystals. Many scattering algorithms have been
developed to calculate the optical properties of ice particles. One of the most known, the Discrete-Dipole Approximation
(DDA, Draine and Flatau, 1994), can be used to calculate the scattering properties of realistic ice crystals and aggregates.

110   Snow hydrometeors with size in the millimeters order of magnitude are found to have low densities and therefore, the Self-
Similar Rayleigh-Gans Approximation (SSRGA, e.g. Hogan and Westbrook, 2014; Hogan et al., 2017; Leinonen et al., 2018a),
that is applicable for "soft spheres", can be used. The term "soft" indicates homogeneous ice particles composed of an ice and
air mixture and a real part of the refractive index close to 1. A well-proven approach is the soft spheroid particle model which
uses the effective medium approximation (EMA) to model the refractive index of ice crystals and aggregates, e.g. the

115   Bruggeman or Maxwell-Garnett models as in Garnett and Larmor (1904). Many studies, e.g. Hogan et al. (2012), have shown
that soft spheroid ice particles can provide quite realistic radar signals in scattering simulations. In the same study, it was also
found that the majority of particles in ice clouds can be well-represented by horizontally aligned oblate spheroids with an axial
ratio value of 0.6.

          In this study, we developed an ice microphysical retrieval scheme using a simple particle model, simulations and novel

120   combination of radar observations for ice hydrometeors. In this way, we are able to simultaneously retrieve median size, aspect
ratio and ice water content of ice particles. For the computation of scattering parameters, the ice particles are assumed to be

spheroids. In this way, we are able to vary parameters such as median size, aspect ratio and ice water content independently, which serve as degrees of freedom of the ice spheroids, and calculate their optical properties without much computational cost as in other scattering algorithms (e.g. DDA, Draine and Flatau, 1994) that are used for more realistic ice crystal shapes

125   simulations. Moreover, using spheroids we can better understand the ambiguities between the aforementioned degrees of freedom. Here, more sophisticated models of specific ice crystals could introduce additional challenges to sort a collection of ice shapes along these degrees of freedom or to define variables like the aspect ratio. The single scattering properties of the ice spheroids are calculated using the T-matrix scattering method as described by e.g. Mishchenko and Travis (1994) and Mishchenko et al. (1996). The averaging over particle orientations and the calculation of radar variables for whole size

130   distributions are done using PyTMatrix (Leinonen, 2014). Combining ice scattering simulations and radar measurements we present an ice microphysics retrieval that resolves the ice water content, the median size and the apparent shape of the detected ice particles. The apparent shape (for simplicity the term shape will be used in this study) describes the average observed aspect ratio which is strongly connected to the particle orientation including small oscillations out of this plane. Although vertically pointing radars are useful for Doppler spectra observations (e.g. Kneifel et al., 2016; Kalesse et al., 2016), they

135   cannot provide sufficient polarimetric measurements, e.g. ZDR, that can be useful to estimate the shape of the ice particles due to their observation geometry. In this work, we can estimate the shape of the ice hydrometeors using ZDR measurements from a scanning weather radar. For size retrievals we use simultaneous range-height indicator (RHI) scans from a scanning cloud radar, 23 km apart from the weather radar, to obtain dual-wavelength observations for the same observation volume. As we aim to use DWR and ZDR measurements from two different locations, we are focused on homogeneous case studies with large

140   clouds and in which hydrometeor attenuation can be considered to be negligible. Therefore, we have selected cloud cross-sections from stratiform snowfall cases where water hydrometeors are unlikely to occur. To exclude liquid hydrometeors and melting layers (ML), an ice mask was developed and applied to the observational dataset. Future studies will also include wet particles to improve the representation of melting and riming processes in numerical weather models.

This publication is organized as follows: In Sect. 2 the instruments used to produce the measurements dataset are

145   described. In Sect. 3 the measurement strategy and the error assessments of the radar observations as well as the T-Matrix scattering simulations are presented in detail. Section 3 demonstrates the methodology to combine DWR and polarimetric measurements along with the scattering simulations in order to retrieve microphysical properties of ice particles. In addition, the attenuation correction methods are described. In Sect. 4, some retrieval results along with their uncertainties as well as statistical results of the ice microphysics retrieval are presented. Furthermore, the limitations of this study and the performance

150   of the ice retrieval in different areas of the radars cross-section are fully discussed. In Sect. 5, the conclusions for the presented approach are drawn.

2 Instruments

This feasibility study to combine two spatially separated weather and cloud radars was conducted in the scope of the IcePolCKa project (Investigation of the initiation of Convection and the Evolution of Precipitation using simulatiOns and

155   poLarimetric radar observations at C- and Ka-band), which is part of the Polarimetric Radar Observations meet Atmospheric Modelling (PROM) Priority Program (Trömel et al., in review, 2021). For the DWR dataset the synergy of two polarimetric radars, the C-band POLDIRAD weather radar at German Aerospace Center (DLR) in Oberpfaffenhofen Munich, and the Ka-band MIRA-35 cloud radar at Ludwig Maximilians University of Munich (LMU), Munich was used. POLDIRAD and MIRA-35 performed coordinated RHI scans towards each other (azimuth angle constant for both radars) at a distance of 23 km

160   between DLR and LMU, monitoring stratiform precipitation events.

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2.1 POLDIRAD

POLDIRAD (Fig. 1, left) is a polarization diversity Doppler weather radar operating at C-band at a frequency of 5.504 GHz (λ = 54.5 mm, λ_1 in Eq. 2). The radar is located at DLR, Oberpfaffenhofen, 23 km southwest of Munich at 48°05'12" N and 11°16'45" E at an altitude of 602.5 m above mean sea level (MSL). Since 1986, POLDIRAD has been operated at the roof

165   of Institute of Atmospheric Physics (IPA), DLR for meteorological research purposes (Schroth et al., 1988). The weather radar consists of a parabolic antenna with a diameter of 4.5 m and a circular beam width of 1°. A magnetron transmitter with a power peak of 400 kW and a Selex ES Germatronik GDRX digital receiver with both linear and logarithmic response are synchronized with the polarization network of the receiver, which can record the linear, elliptic and circular polarization of each radar pulse (Reimann and Hagen, 2016). POLDIRAD has the capability to receive the co- and cross-polar components of the horizontal,

170   vertical, circular and elliptical polarized transmitted electromagnetic waves. In this way it provides several polarimetric variables, e.g. ZDR, ρHV etc., which can be used to obtain additional information about the size, shape, phase, and falling behavior of the hydrometeors in the atmosphere (Straka et al., 2000; Steinert and Chandra, 2009). Depending on its operational mode, the maximum range that can be reached is 300 km (for a pulse repetition frequency of 400 Hz, a pulse duration of 2 μs and a range resolution of 300 m), making it a suitable instrument for nowcasting in the surrounding area of Munich. For the

175   present study POLDIRAD's maximum range was 125 km with a pulse repetition frequency of 1200 Hz, a pulse duration of 1 μs and a range resolution of 150 m. The system can also be operated in the STAR mode (simultaneous transmission and reception). Here, we used the alternate-HV mode (alternate horizontally and vertically polarized transmitted electromagnetic waves) which allows measuring the cross-polar components of the back-scatter matrix. The technical characteristics of POLDIRAD are presented in Table 1.

2.2 MIRA-35

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MIRA-35 (Fig. 1, right) is a Ka-band scanning Doppler cloud radar developed by Metek (Meteorologische Messtechnik GmbH, Elmshorn, Germany) with a frequency of ca. 35.2 GHz and a wavelength λ = 8.5 mm (Görsdorf et al., 2015), which is λ_2 in Eq. (2). The cloud radar, which is operated by the Meteorological Institute Munich (MIM) as part of the Munich Aerosol Cloud Scanner (MACS) project (also referred as miraMACS, Ewald et al., 2019), is located on the roof of the institute at the

185   LMU at 48°08'52.2" N and 11°34'24.2" E and 541 m above MSL. The transmitter consists of a magnetron with a power peak of 30 kW which typically transmits radar pulses of 0.2 μs with a pulse repetition frequency of 5 kHz, corresponding to a range resolution of 30 m. The 1 m diameter antenna dish produces a beam width of 0.6°. The MIRA-35 cloud radar emits horizontally polarized radiation and measures both vertical and horizontal components of the backscattered wave. Hence, it has the capability to perform LDR measurements. The cloud radar usually points to the zenith, but can also perform RHI scans at

190   different azimuths and plan-position indicator (PPI) scans at different elevations angles. Although the maximum radar range for this setup is 30 km, only 23 km range was recorded during the RHI scans performed for the purpose of this study. The technical characteristics of MIRA-35 are presented in Table 1.

195 **Figure 1:** C-band POLDIRAD weather radar (left, photo: Martin Hagen), Ka-band MIRA-35 cloud radar (right, photo: Bernhard Mayer).

Table 1: POLDIRAD and MIRA-35 technical characteristics.

	POLDIRAD	**MIRA-35**
frequency/wavelength	5.5 GHz/ 54.5 mm	35.2 GHz/ 8.5 mm
peak transmitted power	400 kW	30 kW
antenna diameter	4.5 m diameter	1 m diameter
beam width	1.0º	0.6º
transmit mode	pulse duration: 1 µs pulse repetition frequency: 1200 Hz max. range: 125 km range resolution: 150 m	pulse duration: 0.2 µs pulse repetition frequency: 5000 Hz max. range: 30 km range resolution: 30 m
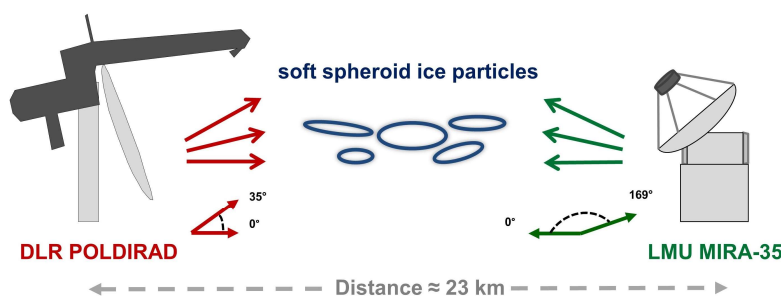
200 **Figure 2:** Geometry of the radar setup. The range of elevation angles is 0°–35° and 0°–169° for POLDIRAD and MIRA-35, respectively.

3 Methodology

This study intends to investigate microphysical properties of ice hydrometeors that are known to affect the type of precipitation (e.g. stratiform or convective) aiming to improve their representation in numerical weather models. To address this, an ice microphysics retrieval scheme has been developed. In this way, the microphysical properties of ice hydrometeors

205 are revealed for stratiform snow precipitation cases. In this section, our approach is presented in detail and demonstrated using a case study example from 30th January 2019 when a snowfall event took place over the Munich area.

3.1 Measurements strategy and data preprocessing

Coordinated RHI measurements with POLDIRAD and MIRA-35 have been collected during three snowfall days on 9th, 10th and 30th January 2019, with some ice particles reaching the ground where both radars are located (602.5 m for POLDIRAD

210 and 541 m for MIRA-35, both heights above MSL). 59 RHI scans were executed from the two radars at almost the same time (time difference between RHIs was estimated less than 15 s) with a temporal resolution which was adjusted to the precipitation rate. POLDIRAD scanned between 0°–35° elevation towards MIRA-35 (northeast direction, azimuth of 73°), while MIRA-35 scanned between 0°–90° elevation towards POLDIRAD (southwest direction, azimuth of 253°) as well as 91°–169° elevation in a backward northeast direction but still inside the common cross-section (Fig. 2). With this setup, the cross-section between

215 the two radars as well as beyond the MIRA-35 position was fully covered to record the development and microphysics of precipitation cells and fall streaks. During the snow events, Z_e measurements from the two radars were performed and interpolated onto a common rectangular grid (50×50 m^2). The 0-height of this grid is defined to be the height above MSL, while POLDIRAD and MIRA-35 locate at 602.5 m and 541 m height above MSL. In Fig. 3a and Fig. 3c, the measured Z_e from

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the two radar systems during the RHI scans from 30th January 2019 at 10:08 UTC is presented. For the MIRA-35 Z_e

220 measurements we applied a calibration offset of 4 dBZ as derived in Ewald et al. (2019). Studying only snow cases no strong effects of hydrometeor attenuation are expected (e.g. Nishikawa et al., 2016). However, an iterative method to estimate hydrometeor attenuation has been developed. Additionally, both Z_e datasets are corrected for gaseous attenuation using the ITU-R P.676-11 formulas provided by International Telecommunication Union (ITU) in September 2016 (ITU-R P.676, 2016). Both methods are fully described in Sect. 3.3. After the interpolation of both radar reflectivities in the common radar grid, we

225 calculated the DWR (Fig. 3b) using Eq. (2). Since DWR is defined as the ratio of Z_e at two wavelengths, it is independent of number concentration N. Therefore, it exploits the difference in the received radar signal due to Mie effects to give size information. To avoid unwanted biases by measurement artefacts, DWR values lower than –5 dB and higher than 20 dB were excluded. Furthermore, errors from other sources, e.g. beam width mismatch effects (beam width 1° for POLDIRAD and 0.6° for MIRA-35), are considered (fully explained in Sect. 3.1.2). Besides DWR measurements, polarimetric observations were

230 used to study the shape of ice particles. POLDIRAD can provide polarimetric measurements of ZDR (Fig. 3d) defined as,

$$ZDR \ [dB] = 10 \cdot log_{10} \left(\frac{Z_H}{Z_V} \right), \tag{3}$$

where,

Z_H: the signal received or reflectivity factor at horizontal polarization,

Z_V: the signal received or reflectivity factor at vertical polarization. Following the definition of ZDR, it is zero if the received

235 signal in both polarization states is the same, i.e. spherical targets. For elongated, azimuthally oriented particles ZDR is found to be greater (oblate particles) or less than zero (vertically aligned prolates), depending on the orientation of their rotational axis to the horizontal polarization state (e.g. Straka et al., 2000). Only ZDR values between –1 dB and 7 dB were considered to be atmospheric hydrometeors signatures. Moreover, the ZDR calibration was validated using additional measurements (described in detail in Sect. 3.1.2). For the ZDR panel (Fig. 3d), reasonable boundaries for optimal visualization purposes were

240 used in the colormap.

When Z_e, ZDR and DWR measurements are combined (Fig. 3), one can already get a first glimpse on the prevalent ice microphysics. Especially below 3 km height, between 20–30 km from POLDIRAD, the large values of Z_e accompanied with the large values of DWR (greater than 5 dB) and the low values of ZDR (lower than 1 dB) indicate the presence of large and quite spherical ice particles. In the following, quantitative ice microphysics will be revealed by the combination of Z_e, DWR

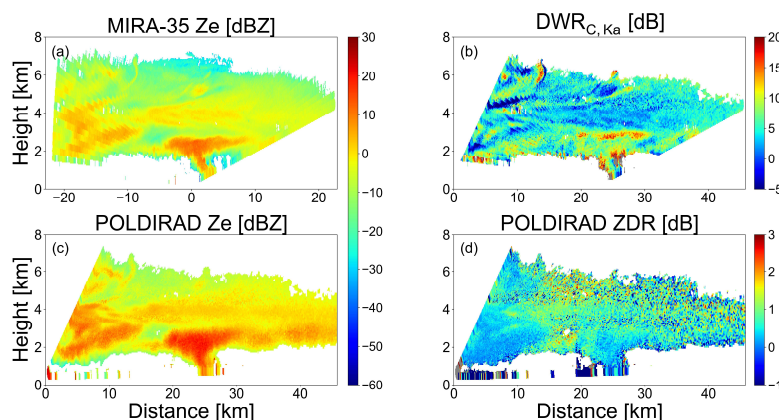245 and ZDR measurements with scattering simulations for a variety of ice particles.

Figure 3: Radar observations of (a, c) MIRA-35 and POLDIRAD Z_e, (b) DWR and (d) POLDIRAD ZDR from 30th January 2019 at 10:08 UTC.

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3.1.1 Ice mask and noise filters application

As already mentioned, the current version of the ice microphysics retrieval only accounts for ice particles. Hence, radar datasets should be filtered accordingly and an ice mask should be applied. The implementation of the ice mask using threshold from polarimetric radar variables, i.e. MIRA-35 LDR, POLDIRAD ZDR and ρHV, as well as temperature sounding data (shown in Fig. 4), are fully presented in Appendix B.
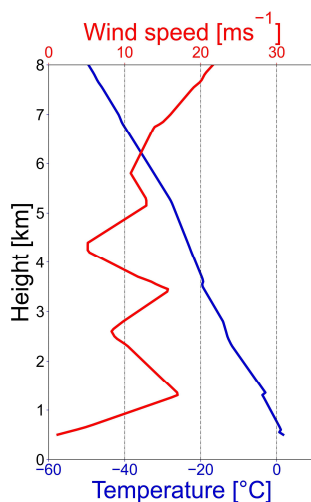
Figure 4: Temperature and wind speed data from Oberschleißheim sounding station (about 13 km north of Munich, source: Deutscher Wetterdienst, data provided by University of Wyoming; http://weather.uwyo.edu/upperair/sounding.html, last access: 10 June 2021) at 12:00 UTC are presented.

3.1.2 Assessment of radar observations errors

Radar measurements are often affected by systematic or random errors. To assess their impact on the ice microphysics retrieval developed in this study we need to investigate possible errors in POLDIRAD and MIRA-35 observations as well as all their sources.

The absolute radiometric calibration of both instruments is an important error source in DWR measurements. While the error of the absolute radiometric calibration of POLDIRAD is estimated to be ±0.5 dB following the validation with an external device (Reimann, 2013), the budget laboratory calibration of MIRA-35 following Ewald et al. (2019) is estimated to be ±1.0 dB.

In order to test for a systematic ZDR bias, we exploited POLDIRAD measurements during vertically pointing scans (also known as birdbath scans, e.g. Gorgucci et al., 1999) in a liquid cloud layer performed on the 4th April 2019. The measurements indicated that ZDR has an offset of about +0.15 dB as ZDR values are expected to be near 0 dB for this case due to the spherical apparent shape of liquid droplets. In Fig. A1 (Appendix A), examples of radar reflectivity Z_e, differential reflectivity ZDR as well as a scatter plot showing the ZDR offset are presented.

Another error that should be considered is the random error, especially for ZDR measurements at low signal levels. To detect and filter out regions with high ZDR noise we compare the local (3 range gates) standard deviation ZDR_{stdv} with the local mean ZDR_{mean}. Subsequently, we only include regions where the signal ZDR_{mean} exceeds the noise ZDR_{stdv} by on magnitude. An example of this approach can be found in Fig. A2 (Appendix A). While we apply the retrieval to all cloud regions, the described ice mask and noise filters are used during the statistical aggregation of retrieval results.

In our case of spatially separated radar instruments, an azimuthal misalignment between both instruments had to be excluded to obtain meaningful DWR measurements. To this end, we performed several solar scans with both instruments in spring 2019 to confirm their azimuthal pointing accuracy (e.g. Reimann and Hagen, 2016). Here, we found an azimuth offset

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280   of -0.2° for POLDIRAD and an azimuth offset of +0.1° for MIRA-35. Consecutive solar scans confirmed the azimuthal pointing accuracy within ±0.1°. Despite the small azimuthal misalignment, the radar beam centroids of both instruments were clearly within the respective other beam width during our measurement period in 2019.

    Besides an azimuthal misalignment, we also analyzed the temporal mismatch between both RHIs as well as the volumetric mismatch in the context of non-uniform beam filling. Although the RHIs from the radars were scheduled to be executed

285   simultaneously, regions within the RHIs are measured at slightly different times by both instruments. This temporal mismatch can lead to slightly different Z_e radar observations from both radars in the context of horizontal advection of an inhomogeneous cloud scene. In the following we used this temporal mismatch to estimate the resulting DWR error for the example case shown in Fig. 3. Using wind data (Fig. 4) from the Oberschleißheim sounding station (source: Deutscher Wetterdienst, data provided by University of Wyoming; http://weather.uwyo.edu/upperair/sounding.html, last access: 10 June 2021), we converted the

290   temporal mismatch (Fig. 5a) between the radar measurements for each pixel in the common radar grid to a spatial difference (Fig. 5c). To estimate the impact of this spatiotemporal mismatch (hereafter spatiotemporal error) we subsequently used these spatial differences to calculate DWR values between pixels in the spatially higher resolved MIRA-35 Z_e measurements (Fig. 5e). Concluding the DWR error assessment, we also analyzed the volumetric mismatch caused by the different beam widths of the two radars. For spatially heterogeneous scenes, this volumetric mismatch can lead to artificial DWR signatures caused

295   by a non-uniform beam filling. Here, the spatially higher resolved MIRA-35 Z_e measurements (30 m range gate length) along the RHI cross section were used as a proxy to obtain the spatial heterogeneity of Z_e perpendicular to the RHI cross section. In a first step, the local beam diameters for each pixel in the common grid are calculated for POLDIRAD (Fig. 5b) and MIRA-35 (Fig. 5d). Then, moving averages along the Z_e cross sections from MIRA-35 are performed using the corresponding local beam diameters. Hence, at each pixel of the common radar grid two averaged MIRA-35 Z_e values are obtained; one

300   corresponding to the local beam diameter of MIRA-35 and one corresponding to the local beam diameter of POLDIRAD. Subtracting the averaged Z_e for each pixel, we were able to estimate the error caused by the volumetric mismatch between both radar beams (Fig. 5f).
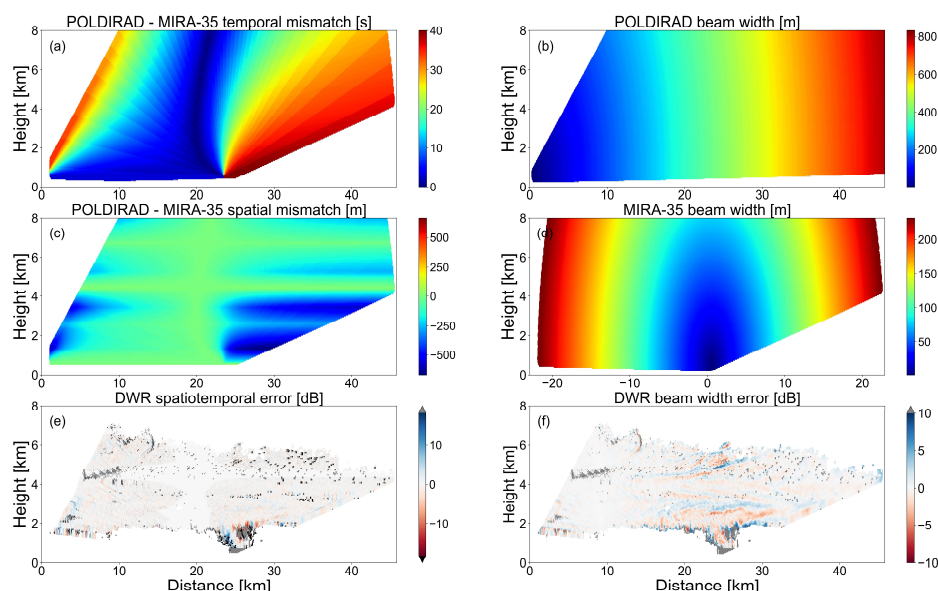
305   **Figure 5:** DWR error assessment due to temporal mismatch (left panels) and volumetric mismatch (right panels). In (a), (c) and (e) panels, the POLDIRAD and MIRA-35 temporal mismatch, the POLDIRAD and MIRA-35 spatial mismatch and the spatiotemporal error in dB are plotted. In (b) and (d) panels, the POLDIRAD and MIRA-35 beam widths are presented, while in panel (f) the estimated DWR error due to the volumetric mismatch is shown. For this plot the data from 30th January 2019 at 10:08 UTC are used. The masked and filtered values in (e) and (f) are plotted with grey color. Black color in panel (e) denotes the additional missing values due to the spatial shift of the radar grid.

310   **3.2 Scattering simulations for ice particles**

Since the simple Rayleigh approximation of Eq. (1a) cannot be used for snow, the scattering calculations were performed using the T-matrix method implemented in the Python package PyTMatrix developed by Leinonen (2014). PyTMatrix is a package that can be easily adjusted to the user's needs via functions and classes regarding the desired preferences for particle shape, size, orientation, particle size distribution (PSD) and wavelength. Calculated scattering parameters, e.g. backscattering

315   cross-section of single particles, can be used to compute radar variables which can then be compared to radar measurements for the purpose of the presented work. As we intended to retrieve the apparent shape (expressed in terms of aspect ratio), the size and the mass of the detected ice hydrometeors, we used aspect ratio (AR), median mass diameter (D_m) of the PSD, and ice water content (IWC) as three degrees of freedom of the simulated ice particles for the development of look-up tables (LUTs). Different LUTs for several angles of radars geometry (Fig. 2) were created. Their values were then interpolated to fit

320   all possible radar viewing geometries and used in the ice retrieval. The a priori assumptions used in the simulations are fully described in the following sub-sections.

Aspect ratio

For the scattering simulations we assumed that ice hydrometeors can be represented by ice spheroids in PyTMatrix. The shape of the particles is defined using the aspect ratio parameter. This is the ratio of the horizontal to rotational axis of the

325   particle. From the description of the simulated ice spheroids in Fig. 6, it is obvious that oblate (shaped like lentil) and prolate particles (shaped like rice) have AR larger and lower than 1.0, respectively, as z axis is selected to be the rotational axis. Using this principle, the representative value of axial ratio = 0.6 from Hogan et al. (2012) is calculated as AR = 1.67 for oblate ice particles in this study. The closest value of our AR simulations grid to 1.67, is AR = 1.60 and therefore, this number was used as a reference value for the simulation plots (Fig. 7, Fig. 8 and Fig. 9a). In this study, we also use the axial ratio (called

330   sphericity S) to compare retrieval results when oblate and prolate ice particles are assumed. S is defined as the ratio of the minor to major axis and therefore, for oblates and prolates is found to be smaller than 1, while for spheres is equal to 1. In this work, all prolate ice particles were assumed to fall with their maximum diameter aligned to the horizontal plane (hereafter referred as horizontally aligned prolates or horizontally aligned prolate ice spheroids) and thus, to be rotated 90° in the yz plane (Fig. 6). Furthermore, small oscillations out of this plane with a standard deviation of 20° are included to consider the
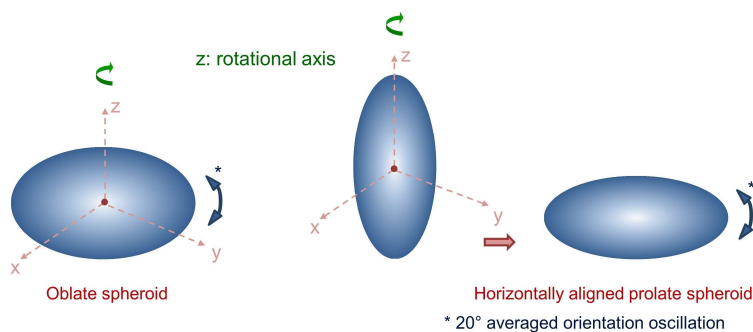
335   flutter of ice crystals.

Figure 6: Description of simulated oblate, vertically aligned prolate and horizontally aligned (rotated 90° in the yz plane) prolate ice spheroids. Only oblate and horizontally aligned prolate ice spheroids were used in the scattering simulations with a 20° standard deviation out of the horizontal plane.

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Mass-size relation

340   In many ice studies, a mass-size relation $m(D_{max})$ can be used to provide information about the mass of the ice crystals and therefore, their effective density with respect to their size. Mass m of an ice particle is connected to its maximum diameter D_{max} with a power-law formula,

$$m(D_{max}) = aD_{max}^b \tag{4}$$

345   where,

a: the prefactor of the $m(D_{max})$, refers to the density scaling at all particles sizes,

b: the exponent of the $m(D_{max})$, relates to the particles shape and growth mechanisms. Several $m(D_{max})$ relations derived from ice studies showed a continuity for the prefactors a and exponents b leading to the derivation of a density factor relation (Mason et al., 2018) from ice unrimed hexagonal columns to dense ice particles and hail. For the mass of the ice particles, the

350   modified $m(D_{max})$ relation of Brown and Francis (Brown and Francis, 1995), BF95, as presented in Hogan et al. (2012) is used in this study,

$$m(D_{max}) = 480 \cdot D_{max}^3, \quad D_{max} < 6.6 \cdot 10^{-5} \ m$$
$$m(D_{max}) = 0.0121 \cdot D_{max}^{1.9}, \quad D_{max} \geq 6.6 \cdot 10^{-5} \ m \tag{5}$$

where,

355   D_{max}: maximum dimension of a spheroid in meters (m),

m: mass of the particle in kilograms (kg). Another $m(D_{max})$ that we use is the aggregates from Yang et al. (2000) (the simple term aggregates will be used in this study). This mass-size relation is used for an aggregated collection of geometrical hexagonal columns. The construction of these aggregates is fully described in Yang and Liou (1998). Assuming spheroids to represent the ice aggregates, the density and thus, the mass of the particles can be calculated using the D_{eq} and D_{max} of Eq.

360   (6). The D_{eq} is used to describe the diameter of a spherical water particle with the same mass as an ice particle with maximum dimension D_{max}.

$$D_{eq} = e^{\sum_{n=0}^4 b_n (ln(D_{max}))^n} \tag{6}$$

where b_n is taken from Table 2 in Yang et al. (2000) and D_{eq} as well D_{max} are in microns.

Particle size distribution

365   In all calculations of our study, ice particle sizes were assumed to follow the normalized Gamma particle size distribution of Bringi and Chandrasekar (2001) with a shape parameter $\mu = 4$:

$$N(D) = N_w \cdot f(\mu) \cdot \left(\frac{D}{D_0}\right)^\mu \cdot e^{\frac{-(3.67+\mu) \cdot D}{D_0}} \quad \text{with } f(\mu) = \frac{6}{3.67^4} \cdot (3.67 + \mu)^{\frac{(\mu+4)}{\Gamma(\mu+4)}}, \tag{7}$$

where,

N_w: the intercept parameter,

370   μ: the shape parameter,

D_0: the Median Volume Diameter,

D: the melted equivalent diameter of the ice particles (defined as D_{eq} in this study). The Median Volume Diameter (D_0) is one of the three parameters used to define the Gamma PSD for the scattering simulations and is the size which separates the PSD in half with respect to volume (defined as: $\int_0^{D_0} D^3 N(D)dD = \frac{1}{2}\int_0^{Dmax} D^3 N(D)dD$). However, the use of Median Mass

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375 Diameter is more common in ice studies. Median Mass Diameter, or Equivalent Median Diameter of the ice particles which

have been melted, or simple, D_m, is the size that splits the PSD in half with respect to mass (defined as: $D_m = \frac{\int_0^{Dmax} D^4 N(D)dD}{\int_0^{Dmax} D^3 N(D)dD}$).

Although DWR can be used to retrieve median size D_0 of PSD without D_0 being much affected by the density of the ice

particles (e.g. Matrosov, 1998; Hogan et al., 2000), it can be also used to retrieve D_m when a mass-size relation is investigated

as D_m is significantly affected by the m(D_{max}) used. For instance, Leroy et al. (2016) found that D_m is significantly affected

380 by the b exponent of the m(D_{max}) and thus, from the mass and the density of ice hydrometeors. As we aim to investigate how

the choice of different parameters affects the results of the ice retrieval (mass, shape and median size), we were also focused

on the D_m median size. Along with the shape parameter μ and intercept parameter N_w, soft spheroids with a defined AR were

used to calculate Z_e and specific attenuation A at both radar wavelengths, and ZDR only at 54.5 mm as this radar variable is

only provided by POLDIRAD. For the refractive index calculation, the Maxwell-Garnett mixing formula was used (e.g.

385 Garnett and Larmor, 1904). In addition to Z_e, A and ZDR simulations, the IWC of the PSD was calculated. The N_w that

corresponds to this value of IWC served as a factor for rescaling to the desired IWC values used for the simulations. The

rescale factor was used for the new estimation of Z_e, A and ZDR. In Fig. 7 an example of the Gamma PSD for intercept

parameter $N_w = 1 \times 10^3$, shape parameter $\mu = 4$, different D_m values and constant AR = 1.60 is presented, showing how D_m and

the shape of the PSD are related. For all calculations, a maximum diameter of 20 mm was used as the maximum size considered

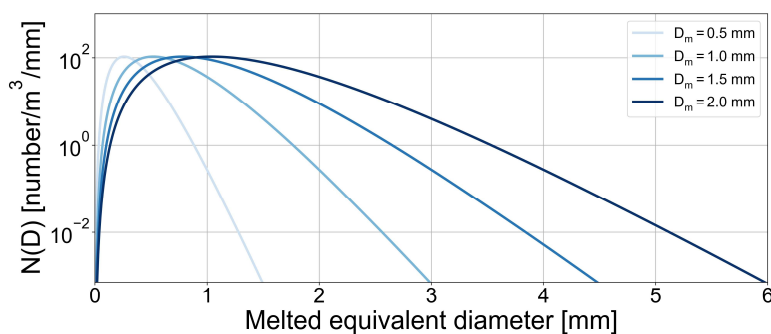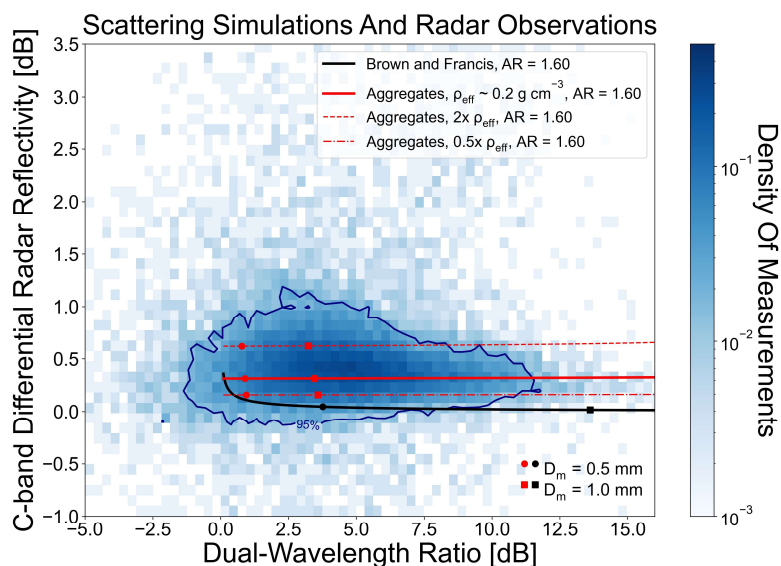390 in the Gamma PSD of the ice particles.

Figure 7: Gamma PSD for different values of D_m, AR = 1.60, $N_w = 1 \times 10^3$, and $\mu = 4$.

Figure 8: Radar observations between 0°–10° elevation angles and scattering simulations for aggregates (red) and BF95 (black) m(D$_{max}$) for AR = 1.60, IWC = 0.50 g m^{-3} and both radar beams simulated to be emitted horizontally. With scatters, the D_m = 0.5 mm and D_m = 1.0 mm are denoted. The 95th percentile of the 2d density histogram is drawn with a dark blue dashed isoline. With red dashed and dash-dotted lines simulations for ice spheroids with double and half the density of aggregates are plotted.

Combining the normalized Gamma PSD and with the m(D$_{max}$) relationships of BF95 and aggregates, scattering simulations show that aggregates produce more pronounced polarimetric signatures due to their higher density and in turn, higher real refractive index. This is illustrated by scattering simulations using both assumptions which are shown along with our radar observations in Fig. 8 (BF95 and aggregates line is plotted with black and solid red color, respectively). These calculations were done for horizontally emitted radar beams and for an aspect ratio of 1.60 and an IWC of 0.50 g m^{-3}. Here, larger DWR values are an indication of larger particles, while ZDR values around 0 are an indication of spherical particles. The same figure also shows scattering simulations for ice spheroids with double and half the density of aggregates m(D$_{max}$) (red dashed and dash-dotted line, respectively). This influence of density on retrieval results will be further discussed in a sensitivity study presented in Sect. 4.3.1. In addition, Fig. 8 also shows our DWR-ZDR measurements for low elevation angles (0°–10°) and for all 59 RHI coordinated scans as a blue shaded density histogram. The dark blue dashed isoline frames the 95th percentile of our radar observations. In Fig. 8 it becomes apparent that the BF95 m(D$_{max}$) relationship cannot explain our radar observations very well as ZDR values drop fast with increasing DWR due to the fast decrease of density with size. Therefore, BF95 will be excluded from further analysis. To compare BF95 with aggregates, some retrieval results using BF95 can be found in Sect. 4.3.1. The mass-size relationship for aggregate ice particles can obviously better explain the density histogram of our DWR-ZDR dataset, especially for particles with DWR > 4 dB.

Look-up tables structure

Using the aggregates m(D$_{max}$), we proceed to the development of LUTs for different values of D_m, AR, IWC and geometries covering the radar elevation angles presented in Fig. 2. D_m of the Gamma PSD was varied between 0.1–3.02 mm in a logarithmic grid of 150 points. A minimum sensitivity limit of DWR = 0.1 dB was used in the simulations leading to different minimum retrievable D_m according to the m(D$_{max}$) and the AR used, but also the radar viewing geometry (more details about this topic can be found in Appendix C). IWC was varied between 0.00001−1 g m^{-3} in a logarithmic grid of 101 points. Scattering properties for spheroid oblate and horizontally aligned prolate ice particles were calculated and saved in separated LUTs with the aspect ratio ranging between 1.0−8.0 (values: 1.0, 1.25, 1.6, 2.0, 2.5, 3.2, 4.0, 5.0, 6.2, 8.0) for the

oblates and the inverse values for the horizontally aligned prolate particles. Two examples of the scattering simulations are presented in Fig. 9. For the creation of both panels we assumed the simulated radar beams to be transmitted horizontally

425 towards each other (horizontal-horizontal geometry). For Fig. 9a an AR = 1.60 was chosen. Radar reflectivity Z_e at C-band as well as DWR were calculated for different D_m values and different values of IWC of the PSD. Larger values of radar reflectivity Z at C-band are observed for larger values of D_m and larger IWC. Furthermore, as D_m increases, DWR increases as well, indicating the sensitivity of DWR to the size. An important remark is that for constant D_m, DWR remains invariant to varied IWC. For Fig. 9b we chose IWC to be 0.50 g m^{-3}. ZDR values are found to be invariant for all simulated values of IWC

430 when AR, D_m and shape parameter μ of PSD as well as the m(D_{max}) remained the same. All the aforementioned principles are then used to implement a method for retrieving ice microphysics information from radar measurements.
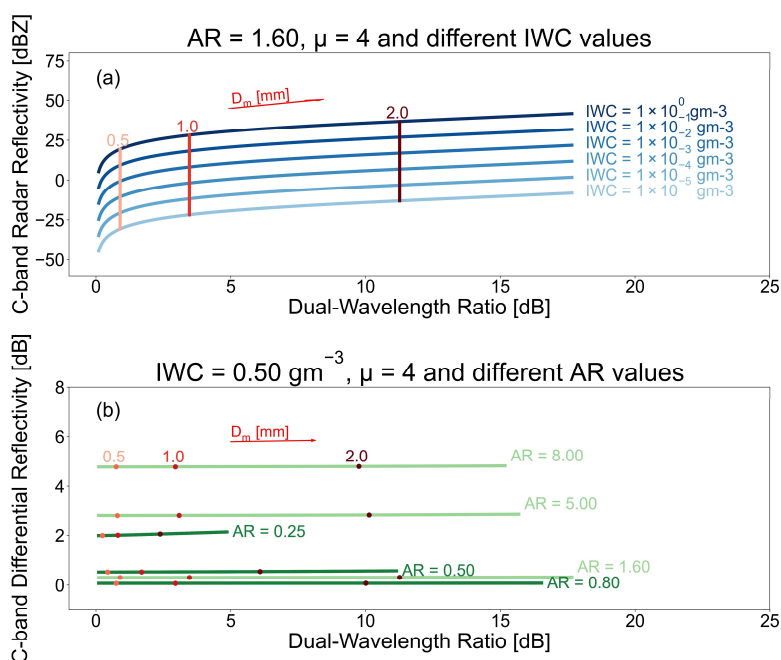
Figure 9: Scattering simulations for (a) radar reflectivity and (b) differential radar reflectivity vs. dual-wavelength ratio for horizontally
435 aligned spheroid ice particles, horizontal-horizontal geometry, shape parameter $\mu = 4$ and aggregates m(D_{max}). For the upper panel the AR was chosen 1.60, while for the bottom panel the IWC was chosen 0.50 g m^{-3}. The light green and the dark green color lines denote simulations for oblates and horizontally aligned prolates, respectively.

3.3 Correction of attenuation

Before using the radar observations for the development of the ice retrieval algorithm, they need to be corrected for beam
440 propagation effects. One major influence is the attenuation by atmospheric gases and by hydrometeors. This holds especially true for the Ka-band radar measurements. Although snow attenuation in C-band can be mostly neglected especially for low density particles and low snowfall rates (Battan, 1973; Table 6.4), the corrections will be done in both radar bands for reliability purposes.

3.3.1 Gaseous attenuation

445 Both MIRA-35 and POLDIRAD radar reflectivities are corrected for attenuation caused by atmospheric gases. Atmospheric water vapor can cause considerable attenuation of radar signals especially at the higher frequency (35.2 GHz) of our instrumentation. The gaseous attenuation for both radar bands is calculated using line-by-line formulas proposed by ITU-

R P.676-11 model (ITU-R P.676, 2016). The corrections are implemented for oxygen and water vapor lines where the attenuation is expected to be significant. The gaseous attenuation formulas use atmospheric pressure, temperature and relative

450   humidity for each RHI, obtained from ECMWF ERA5 reanalysis data (Hersbach et al., 2018).

3.3.2 Hydrometeors attenuation

Next to the gaseous attenuation, the hydrometeor attenuation needs to be considered, too. For this purpose, an iterative approach using the ice microphysics results is developed. In this way, both radar reflectivities are corrected to mitigate the impact of hydrometeor attenuation on the ice microphysics retrieval. For this approach, the retrieval algorithm is used twice.

455   A more detailed description of this method will be presented in Sect. 3.4 along with the developed ice retrieval scheme.

3.4 Development of ice microphysical retrieval

For the development of the ice retrieval scheme, radar measurements of Z_e, ZDR and DWR are compared with the PyTMatrix scattering simulations described in Sect. 3.2. The retrieved parameters are IWC in g m^{-3}, D_m of the PSD in mm, and AR of the measured hydrometeors. Considering their different ranges, we used normalized differences between simulated

460   and measured values of DWR as well as Z_e and ZDR at C-band. By minimizing these differences, the best-fitting microphysical parameters are found. The microphysics retrieval is implemented in two steps using the minimization of the two following cost functions:

$$min\,J_1(D_m, AR) = norm\big(\Delta ZDR(D_m, AR)\big) + norm\big(\Delta DWR(D_m, AR)\big)$$
$$min\,J_2(IWC) = norm(\Delta Z_{e_C}(IWC)) \tag{8}$$

465   where with Δ the difference between simulated and measured parameter is denoted.

Both ZDR and DWR are invariant to IWC when same values of D_m and AR are used. Therefore, D_m and AR are found in the first step, whilst the IWC is constrained in the second step. While the DWR merely contributes to the retrieval of D_m, the ZDR measurement narrows down the solution of aspect ratio of the ice particles. As Z_e at C-band is less affected by attenuation compared to Ka-band, it is better suited to estimate the IWC. After the retrieval of size D_m and shape AR in the

470   first step, the algorithm continues with these values with the retrieval of IWC in the second step by minimizing the cost function J_2 in the LUT. Completing these two steps, the microphysics retrieval has retrieved not only preliminary D_m, AR and IWC but also the specific attenuation A at both radar bands which is used for the total attenuation estimation. As the ice retrieval produces results using radar measurements interpolated onto a cartesian grid, the estimated A at C- and Ka-band needs to be converted from cartesian to the original polar coordinates for the calculation of the total attenuation for each radar band. After

475   A, in polar coordinates, is integrated along the radar beams, the total attenuation for each radar dataset is calculated and converted back from polar to cartesian coordinates. Then, it is used to correct Z_e for both radars. In the next step, the final microphysical parameters such as AR, IWC and D_m are retrieved using the corrected Z_e from both bands as well as ZDR from POLDIRAD. Figure 10 shows the process of attenuation correction and retrieval in more detail. An output example of the ice microphysics retrieval scheme for the already introduced case study from 30th January 2019 at 10:08 UTC (Fig. 11–12) can be

480   found in Sect. 4.1. The total attenuation for this case study is presented as a supplement material accompanying this paper.
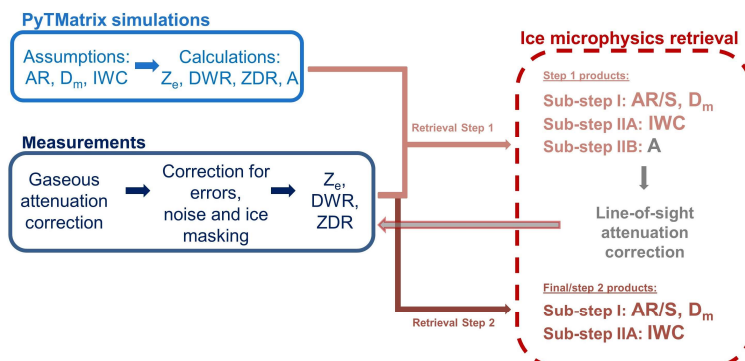
Figure 10: Ice microphysics flowchart. The dark blue color refers to radar observations. The light blue color is for scattering simulations and the red dotted rounded rectangle gives information about the ice microphysics retrieval scheme. With gray color the total attenuation correction is denoted.

4 Results

4.1 Retrieval of ice microphysics

59 pairs of coordinated RHI measurements from POLDIRAD and MIRA-35 were investigated. Here, we use a case study from 30th January 2019 at 10:08 UTC, already presented before, to demonstrate the output of the ice microphysics retrieval scheme. The microphysical properties of the detected hydrometeors are shown in Fig. 11 (assuming oblate ice spheroids and LUTs for different radar viewing geometries) and Fig. 12 (assuming horizontally aligned prolate ice spheroids and LUTs for different radar viewing geometries). In Fig. 11a and Fig. 12a, the retrieved AR is presented. Both plots suggest that in the cross-section of the cloud between the two radars and especially, in the area which is below 3 km height at a distance 0–12 km away from POLDIRAD, more spherical ice hydrometeors are present. Further away at a distance 12–20 km from POLDIRAD, more aspherical particles with AR = 4.0 and AR = 0.3, for oblates and horizontally aligned prolates respectively, were found. The same result is also supported from S plots in Fig. 11c and Fig. 12c where $S > 0.6$ for the spherical particles between 0–12 km distance and $S < 0.6$ for the aspherical particles between 12–20 km distance. The retrieved AR and S could explain well the ZDR measurements in Fig. 3d where more spherical particles have ZDR < 0.5 dB, while aspherical particles have ZDR > 0.5 dB. Overall, the ZDR measurements could be replicated better with the retrieval results using oblate ice spheroids with RMSE = 0.18 dB (with the term RMSE, the mean Root Mean Square Error over all grid points is meant) between the fitted and measured ZDR for the whole scene, against RMSE = 0.25 dB when horizontally aligned prolate ice spheroids were used. In Fig. 11b and Fig. 12b, the retrieved D_m increasing towards the ground is an indication that large ice particles are present below 3km height compared to smaller particles that are dominant at higher altitudes. This is obvious in both oblates and horizontally aligned prolates results. Comparing this plot with the DWR measurements from Fig. 3b, we observe that the retrieved D_m could reasonably explain DWR. The correlation between DWR and D_m is found again to be better when oblate ice spheroids are used. The RMSE for the fitted-simulated and measured DWR is 0.54 dB when ice oblates are used in the simulations, while RMSE = 0.81 dB when the ice particles were assumed horizontally aligned prolates. Although DWR and ZDR measurements are combined for the shape and size retrieval (minimization of J_1 in Eq. 8), the spatial patterns agreement between DWR-D_m and ZDR-AR/S plots indicate the strong correlation of DWR and ZDR with size and shape, respectively.

Figure 11d and Fig. 12d show the results of the retrieved IWC. Areas with positive POLDIRAD Z_e values in Fig. 3c correspond to IWC values higher than 1×10^{-3} g m^{-3}. Hence, the sensitivity of Z_e to mass of the ice particles is again indicated for both spheroid shapes (oblates and horizontally aligned prolates). Nevertheless, the Z_e RMSE for horizontally aligned prolate ice

particles, is 0.34 dB whilst the RMSE is found 0.19 dB when ice oblates are used. All RMSE which serve as residual values for the ice retrieval are collected in Table 2. The lowest RMSE are found when oblate ice spheroids are assumed. Figure 13

515 shows averaged profiles of D_m for both shape assumptions for the whole cloud cross-section measured on 30th January 2019 at 10:08 UTC. The averaged D_m profile for oblate ice spheroids is plotted in dark red, while the averaged D_m profile for horizontally aligned prolate ice spheroids is plotted in red. Between the two shape assumptions the prolate assumption gives an on average by 0.36 mm larger D_m profile. The respective shaded areas indicate the estimated error of D_m when the calibration uncertainty of Z_e and estimates of the spatiotemporal and non-uniform beam filling error discussed in Sec. 3.1.2

520 are considered. Here, the measurement errors are propagated to D_m using a min-max approach: after the sum of the Z_e calibration uncertainties for POLDIRAD (±0.5 dBZ) and MIRA-35 (±1.0 dBZ) is added and subtracted to DWR values, the DWR error estimates for the spatiotemporal and non-uniform beam filling error are added. In that way we obtain two additional D_m profiles which serve as upper and lower boundary for the D_m estimate. For the investigated case study, the average D_m error is estimated to be ±0.44 mm for oblate spheroids, while it is estimated to be ±0.48 mm for prolate spheroids.

525
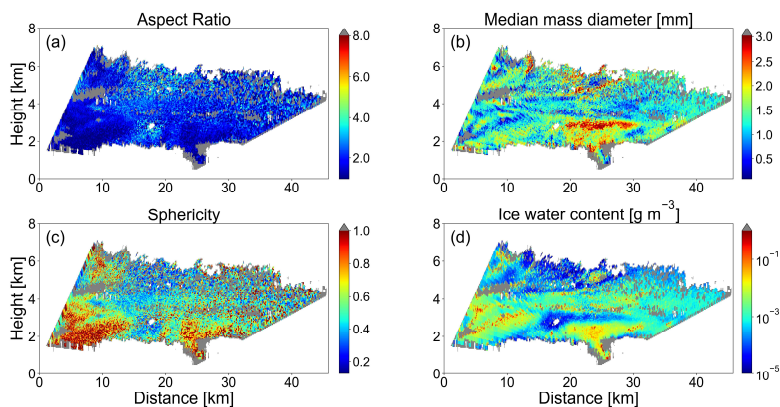
Figure 11: Retrieved (a) AR, (b) D_m, (c) S and (d) IWC for oblates ice particles for 30th January 2019 at 10:08 UTC using aggregates m(D_{max}). Areas where masked and filtered measurement values locate are plotted with grey color.
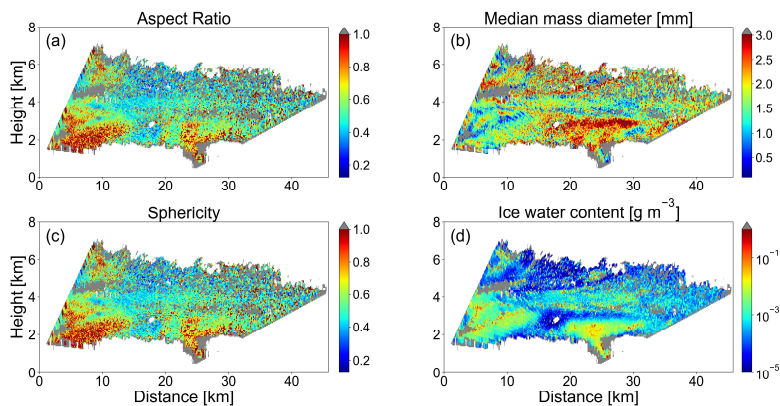

530

Figure 12: Retrieved (a) AR, (b) D_m, (c) S and (d) IWC for horizontally aligned prolate ice particles for 30th January 2019 at 10:08 UTC using aggregates m(D_{max}). Areas where masked and filtered measurement values locate are plotted with grey color.

535 **Table 2:** RMSE values between simulated and observed ZDR, DWR, Z_e values after the retrieval using oblate and horizontally aligned prolate ice spheroids and aggregates m(D_{max}) assumption.

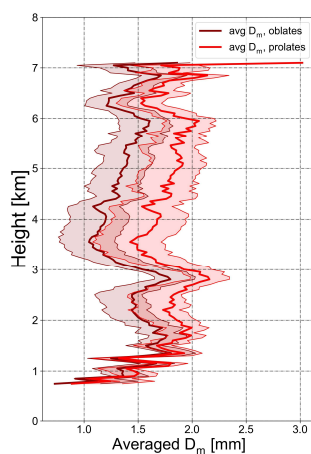| Shape assumption	Parameter	RMSE
Oblates	DWR	0.54 dB
	ZDR	0.18 dB
	Z_e	0.19 dB
Horizontally aligned prolates	DWR	0.81 dB
	ZDR	0.25 dB
	Z_e	0.34 dB

Figure 13: Averaged profiles of the retrieved D_m for the oblate and the horizontally aligned prolate shape assumption and the aggregate
m(D_{max}) relationship derived from Fig. 11b and Fig. 12b for the case measured on 30th January 2019 at 10:08 UTC. The shaded areas
540 indicate the estimated D_m error when the calibration uncertainty of Z_e and estimates of the spatiotemporal and non-uniform beam filling error
are considered.

4.2 Statistical overview

After investigating 59 pairs of RHI scans from three different snow events, we created stacked histograms with respect to
temperature for a deeper insight of the retrieval. Particularly, all RHI measurements from 9th January 2019 between
545 11:18−15:08 UTC, 10th January 2019 between 09:08−17:08 UTC and 30th January 2019 between 10:08−12:38 UTC were
compared to scattering simulations in LUTs for oblate and horizontally aligned prolate ice particles. Statistical results of the
retrieved S, D_m and IWC are presented in Fig. 14. In the first three panels of this figure, results for the retrieved parameters
assuming oblate particles are presented, while in the last three panels, the same kind of results for horizontally aligned ice
prolates are shown. At first glance, the majority of ice hydrometeors are found to be neither very spherical nor very elongated
550 (green color panel plots, first column in Fig. 14). When oblate ice spheroids are used in the scattering simulations, the greater
part of retrieved S values is found to range from 0.3 to 0.6. With the assumption that ice hydrometeors can be represented by
horizontally aligned prolates, the distribution is narrower with the majority of the detected particles to have S values ranging
between 0.4−0.6. From the D_m retrieval (red color panel plots, second column in Fig. 14), the results for oblates showed a
narrower distribution shifted towards lower median mass diameters, while for horizontally aligned prolates the retrieved values
555 are more broadly distributed towards larger values of D_m (median value of both distributions can be found in Table 3). The
histograms for the retrieved IWC (blue color plot panels, third column in Fig. 14) are plotted using logarithmic x axis for
visualization purposes. The statistical results showed that the greater part of the detected ice hydrometeors is found to have
IWC values $1\times10^{-4}-1\times10^{-1}$ g m^{-3} (−4 to −1 in the logarithmic axis) when oblate ice spheroids were assumed. For horizontally
aligned prolate ice particles, most of the detected ice hydrometeors are found to have IWC values between $3\times10^{-5}-3\times10^{-2}$ g
560 m^{-3} (−4.5 to −1.5 in the logarithmic axis). The spikes in both D_m and IWC histograms are merely caused from the strong
discrepancies between simulated and measured radar variables during the minimization of J_1 and J_2 in Eq. (8), i.e. negative
measured values of DWR, while the minimum value 0.1 dB was used in the simulations (see also Appendix C). The different

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color shades in all panel plots denote the different temperature groups in which the detected hydrometeors are separated. For both shape assumptions, it is observed that when temperature drops below −25 °C ice hydrometeors populations with IWC < 3×10⁻³ g m⁻³ dominate the particles distribution. Furthermore, for higher temperatures the greater part of the $\log_{10}$IWC distribution is shifted towards larger values in the logarithmic axis, denoting larger retrieved IWC.

For better interpretation of the ice retrieval results during the three investigated snow events, we further proceed with the calculation of some descriptive statistics presented in Table 3. The median of the retrieved properties for the observed particles distributions was calculated. With the assumption that the detected ice particles can be represented by oblate spheroids, we calculated the median retrieved sphericity $S = 0.400$, the median retrieved $D_m = 0.98$ mm and the median retrieved IWC = $4×10^{-3}$ g m⁻³. On the contrary, when the observed hydrometeors were assumed to be horizontally aligned prolate spheroids, the median retrieved sphericity, the median retrieved median mass diameter and the median retrieved ice water content, were found $S = 0.500$, $D_m = 1.45$ mm and IWC = $1.3×10^{-3}$ g m⁻³, respectively. Although the two median S are quite close, there are differences in the median D_m and IWC between oblates and horizontally aligned prolates. For the latter, the median D_m was calculated larger and the IWC was calculated lower than the respective values for oblate ice spheroids. Therefore, the shape assumption seemed to affect the retrieved microphysical properties of the ice particles (also shown in Sect. 4.1). In Table 3 the 10th and 90th percentile of the detected hydrometeors retrieved parameters can be also found.
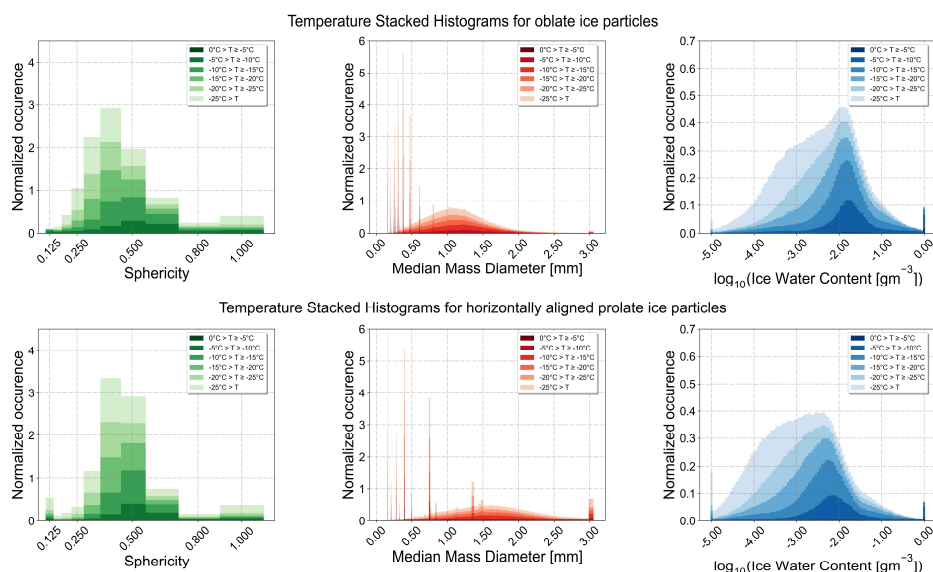
Figure 14: Temperature stacked histograms for oblates and horizontally aligned prolates ice particles using the retrieval output for aggregates m(Dmax) from three days of measurements.

Table 3: Statistical description of the retrieved parameters for oblate and horizontally aligned prolate ice spheroids.

Shape assumption	Statistical Description	Sphericity	Median Mass Diameter [mm]	Ice Water Content [g m⁻³]
Oblates	Median	0.400	0.98	$4×10^{-3}$
	10th percentile	0.312	0.31	$2×10^{-4}$
	90th percentile	0.800	1.67	$45×10^{-3}$
Horizontally aligned prolates	Median	0.500	1.45	$1.3×10^{-3}$
	10th percentile	0.312	0.40	$0.7×10^{-4}$
	90th percentile	0.800	2.52	$21×10^{-3}$

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One limitation of the current version of the ice retrieval is the need to make two significant a priori assumptions about the particle properties. The first assumption (discussed in Sect. 4.1) concerns the choice if we assume oblate or horizontally aligned prolate ice spheroids. In addition to the shape, we have to assume a suitable $m(D_{max})$ relationship for the prevalent ice particles. For the three investigated snow events the selection of aggregates $m(D_{max})$ over the BF95 has been partially discussed in Sect. 3.2. An extended explanation for this selection is presented in Sect. 4.3.1.

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4.3.1 Unknown mass-size relationship

From the two $m(D_{max})$ relations initially used in the scattering simulations, only the aggregates $m(D_{max})$ was systematically used for the statistical analysis of this study. The BF95 mass-size relation was found to model too low ice particle densities. Although ice crystals are known to have lower densities when they grow larger (except for graupel or hail), BF95 prescribes near-zero density values for large particles. This leads to very low simulated ZDR values with increasing particles size (Fig. 8). The ice retrieval results for the examined case study, using LUTs for oblate ice crystals and BF95 mass-size relation, are presented in Fig. 15 along with the residual values of ZDR, DWR and Z_e, expressed using RMSE values, in Table 4. The RMSE for ZDR and Z_e are quite low and in the same order of magnitude like the RMSE for aggregates $m(D_{max})$ for both oblate and horizontally aligned prolate shape assumptions (Table 2). However, the retrieved AR and S (Fig. 15a and Fig. 15c) could not really explain ZDR measurements (Fig. 3d). The AR is almost unrealistically high, suggesting e.g. plates, for the greater part of the cloud cross-section using BF95 $m(D_{max})$. The RMSE for DWR with 2.84 dB was found to be quite high, suggesting that the retrieved D_m (Fig. 15b) could not replicate DWR measurements (Fig. 3b). On the other hand, IWC (Fig. 15d) showed a good agreement to the radar measurements as it could explain well POLDIRAD Z_e (Fig. 3c). The retrieved values were found to be larger than the IWC values retrieved using the aggregates $m(D_{max})$ for both shape assumptions.

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Overall, the plots of retrieved parameters as well as the RMSE for ZDR, DWR and Z_e reveal that the output of the ice retrieval using the aggregates $m(D_{max})$ and LUTs for oblate ice spheroids (Fig. 11 and Table 2) were found to better explain the radar observations compared to the BF95 assumption. Figure 16 shows the residuals between the simulated and measured DWR for aggregates (Fig. 16a) and BF95 $m(D_{max})$ (Fig. 16b). For aggregates $m(D_{max})$, the residuals are evenly distributed around 0 (mean value of +0.08 dB) suggesting that this mass-size relation can better explain our measurements in this case. In contrast, the measured DWR appeared to be higher than the simulated one for BF95 for the larger part of the cloud cross-section (reddish areas) with a mean value of –1.45 dB.

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To further investigate the significance of the $m(D_{max})$ relation for the retrieval result, we conducted a small sensitivity study using the aggregates assumption from Yang et al. (2000) which suggests an almost constant effective density, ρ_{eff}, (approximately $\rho_{eff} = 0.2$ g cm^{-3}) of ice particles with increasing size. Using this value as a reference, we created LUTs for oblate ice particles, once with twice and once with half the density of the aggregates mass-size relation (simulations shown also in Fig. 8 with red dashed and dash-dotted lines). Retrieval results for ice oblates with twice the density are shown in the top panels of Fig. 17, while the bottom panels show the results for ice oblates with half the density of aggregates. Corresponding RMSE values for Z_e are given in Table 4. Focusing on the IWC retrieval, we obtain lower IWC values (with an RMSE = 0.28 dB for Z_e) for ice particles with twice the density of aggregates than the IWC values retrieved in Fig. 11d. Analogously, we retrieve larger IWC (with an RMSE = 0.15 dB for Z_e) for ice particles with half the density of aggregates. In Table 4 the residual values expressed as RMSE for DWR and ZDR can also be found. When the ice spheroids are denser, the DWR RMSE is 0.56 dB, while the DWR RMSE is 0.64 dB for the less dense ice spheroids. The RMSE for ZDR are found to be the same in both cases. However, the denser aggregates suggest the presence of more spherical particles compared to more aspherical particles when less dense aggregates are assumed.

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The aforementioned examples indicate the limitations of the ice retrieval to provide realistic microphysics information when a fixed mass-size relation is used. To overcome this weakness, but still keep our approach simple, a combination of

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m(D_{max}) relations considering the different behavior of large/softer and small/denser ice particles would help the retrieval producing more realistic microphysics results. Additional measurements (e.g. Doppler velocity), in a possible extension of this method, might be able to replace the fixed m(D_{max}) assumption used in this approach with a whole set of m(D_{max}) depending on the average ice particles density affected by the environment in which they are formed.
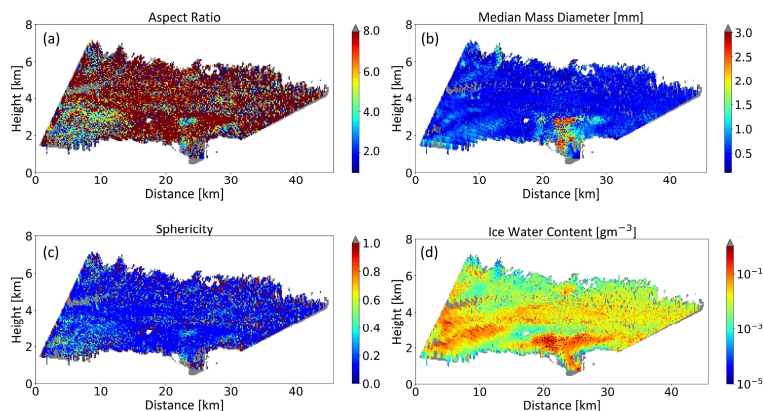
Figure 15: Retrieved (a) AR, (b) D_m, (c) S and (d) IWC for oblates ice particles for 30th January 2019 at 10:08 UTC using BF95 m(D_{max}). Areas where masked and filtered measurement values locate are plotted with grey color.
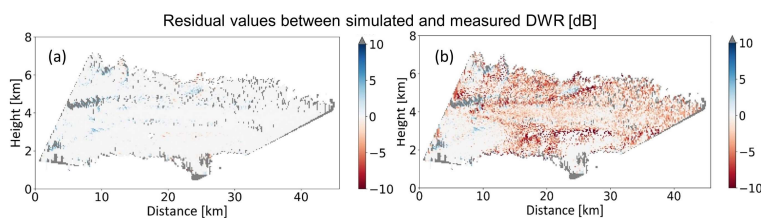
Figure 16: Difference (residuals) between simulated and measured values of DWR for (a) aggregates and (b) BF95 m(D_{max}) for 30th January 2019 at 10:08 UTC. Areas where masked and filtered measurement values locate are plotted with grey color.
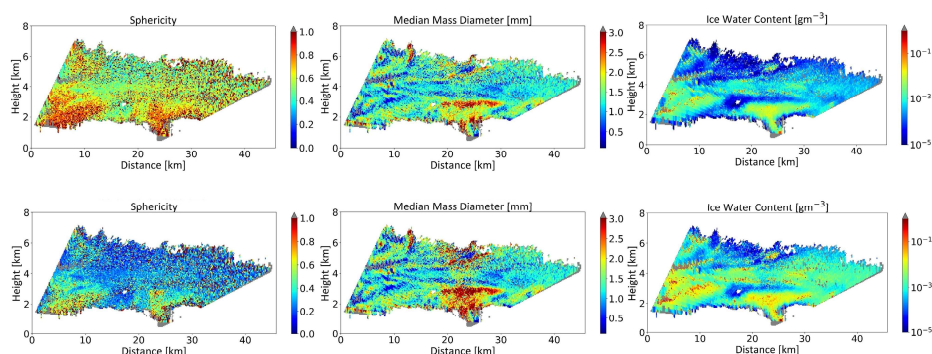
Figure 17: Ice microphysics results for oblate ice spheroids 2 times denser (top panels) and 0.5 times less dense (bottom panels) than aggregates from Yang et al. (2000). Areas where masked and filtered measurement values locate are plotted with grey color.

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645 **Table 4:** RMSE values for simulated ZDR, DWR, Z_e compared to original observations for oblate ice spheroids and different m(D$_{max}$) assumption.

m(D$_{max}$) assumption	Parameter	RMSE
BF95	DWR	2.84 dB
	ZDR	0.24 dB
	Z_e	0.15 dB
Aggregates 2 times denser than Yang et al. (2000)	DWR	0.56 dB
	ZDR	0.19 dB
	Z_e	0.28 dB
Aggregates 0.5 times less dense than Yang et al. (2000)	DWR	0.64 dB
	ZDR	0.19 dB
	Z_e	0.15 dB

4.3.2 Particles shape and viewing geometry

The retrieval results in both Fig. 11 and Fig. 12 showed that some areas are affected more than others from the shape assumption inside the cloud cross-section. For instance, in the region above the Ka-band radar, the retrieved D_m was found to be lower when oblate ice spheroids were used compared to horizontally aligned prolates. Conversely, the lower values of D_m

650 for ice oblates lead to a higher retrieved IWC. In these areas, the use of the polarimetric signature from POLDIRAD, i.e. ZDR, is furthermore found to be crucial: not only to constrain the shape but also to reduce ambiguities between size and mass of the detected ice hydrometeors. To further evaluate the performance of the retrieval, 2d density histograms between retrieved D_m and measured DWR were created for the oblate shape assumption, including all 59 RHI scans. The histograms are presented in Fig. 18 for elevation angles $\theta_C = \theta_{Ka} = 30°$ (Fig. 18a) and $\theta_C = 10°$, $\theta_{Ka} = 90°$ (Fig 18b). The first observation geometry (Fig.

655 18a) is a region located between both radar instruments, while the second one (Fig. 18b) located directly above the Ka-band radar site. On top the density histograms, the DWR-D$_m$ simulations for different values of AR are plotted with grey lines. In (Fig. 18a), the simulations as well as the retrieved D_m are more closely distributed than in (Fig. 18b). The close distribution of the DWR-D$_m$ lines in Fig. 18a suggests that the shape and the size retrieval are not strongly correlated in the region between both radar systems since the simulated DWR does not change much with AR. In the region above the Ka-band cloud radar,

660 however, polarimetric measurements from the C-band weather radar POLDIRAD (i.e. ZDR) help to narrow down the solution space of the size retrieval (Fig. 18b) by providing information about the ice particle shape. This behavior is fully explained in Fig. 19 where the radar beams passing through ice oblate spheroids are drawn. In Fig. 19a, the radar beams from the two instruments penetrate oblate spheroids with different AR with the same elevation angle $\theta_C = \theta_{Ka} = 30°$. From the radar viewing geometry this is supposed to happen in cloud regions located between both radar instrument. In Fig. 19b, the elevation angle

665 for C-band is $\theta_C = 10°$, while the Ka-band points to zenith with $\theta_{Ka} = 90°$. In both cases, the radar beams penetrate three different shaped ice oblates that are aligned with their maximum dimension in the horizontal plane and which are chosen to have the same D_{max}. In Fig. 19a, the length of the Ka-band beam does not change dramatically inside the oblate ice particle. In Fig. 19b, however, the MIRA-35 beam length through the oblate ice particle, and hence the DWR, is very sensitive on the aspect ratio. Therefore, the DWR-D$_m$ relationship becomes quite sensitive to AR in this area, especially when particles are

670 assumed to be horizontally oriented. From similar geometric considerations, the region between both radars at very low elevation angles is another region in which the size retrieval benefits from the AR constraint. In the case of variable ice crystal shapes, ZDR from POLDIRAD is, thus, very helpful for the D_m estimation.

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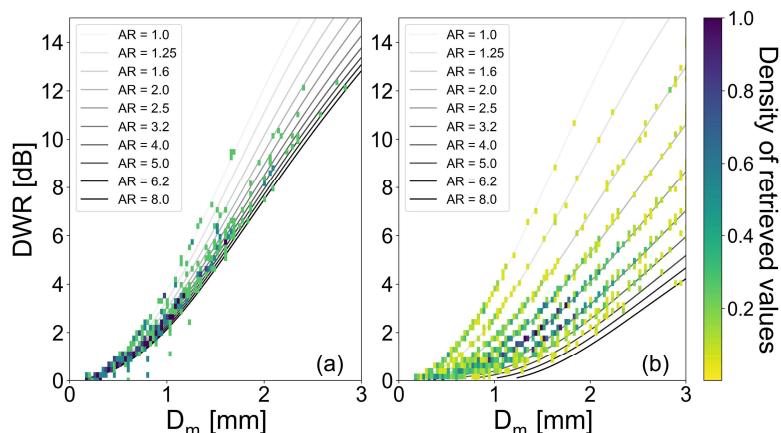
Figure 18: 2d density histograms between retrieved D_m and measured DWR for different observation geometries. (a) Between both radars with $\theta_C = \theta_{Ka} = 30°$ and (b) above the Ka-band radar $\theta_C = 10°$, $\theta_{Ka} = 90°$. With grey lines the DWR and D_m simulations are plotted for different values of AR using oblate ice spheroids and aggregates m(D_{max}).
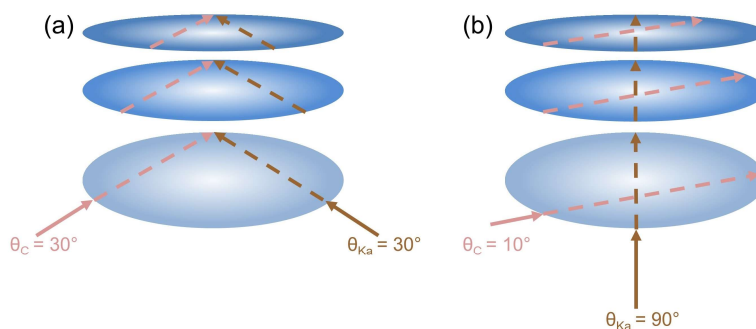
Figure 19: Radar beam geometries through oblate ice spheroids with different AR values for (a) $\theta_C = \theta_{Ka} = 30°$ and (b) $\theta_C = 10°$, $\theta_{Ka} = 90°$.

5 Conclusion

In the present study, we combined dual-wavelength radar observations from the spatially separated weather radar POLDIRAD and cloud radar MIRA-35 to estimate the size of ice hydrometeors. Introducing a novel approach, we used the differential radar reflectivity from the weather radar to constrain the particle shape during the particle size retrieval. To this end, we calculated scattering properties for a variety of ice particles using PyTMatrix with AR, D_m and IWC as degrees of freedom for the simulated ice spheroids. Scattering simulations for all possible viewing geometries between the cross-section of the radar instruments were then compiled in LUTs and compared to radar observations implementing an ice microphysics retrieval scheme. Using the microphysics retrieval, we obtained AR/S, D_m and IWC in ice cloud regions. Next to these parameters, we also calculated the attenuation by ice hydrometeors and corrected our radar observations. Besides attenuation, the uncertainty of the radar calibration has been considered. In addition, the impact of the spatiotemporal mismatch between RHI scans and the volumetric mismatch between the radar beams on the measured DWR were analyzed. All aforementioned errors were subsequently propagated through the retrieval to obtain an error estimation.

Three snow events from January 2019 were used to test the ice microphysical retrieval. The retrieved parameters for shape, size and mass could reasonably explain the radar measurements of ZDR, DWR and Z_e when the detected ice particles were assumed to be represented by oblate spheroids (smaller RMSE and retrieval errors than for horizontally aligned prolates) and

when the aggregates $m(D_{max})$ from Yang et al. (2000), instead of the well-known BF95 assumption, was used. In the course of this study, the density of ice spheroids from BF95 turned out to be too low with increasing size. For that reason, BF95 could not produce pronounced polarimetric signals. Although the aggregates $m(D_{max})$ could better explain our ZDR-DWR observations, their assumption suggests an almost constant density with increasing particle size, i.e. small ice crystals (columns

700   or plates) appear to have the same density as larger ice particles (aggregates). Therefore, we still need a $m(D_{max})$ relation which describes a more realistic function between density and size. Here, additional measurements, e.g. Doppler velocity of ice hydrometeors, could be exploited in future studies to provide a more variable $m(D_{max})$ relation instead of a fixed one. In conclusion, the assumption of the $m(D_{max})$ relation together with the decision for oblate or prolate particles had the biggest impact on the retrieval. Within its uncertainty, the radar calibration has only secondary importance, while errors due to

705   spatiotemporal and volumetric mismatches are considered to be even less important to the average retrieval profile. Non-uniform beam filling effects, however, can locally have strong impacts (of several dB) on DWR measurements. Subsequent studies certainly need to explore this effect for spatially separated radars in more detail and need to develop techniques to detect and filter out these regions.

     Nevertheless, promising microphysics information can be obtained from the combination of dual-wavelength and

710   polarimetric measurements from spatially separated radars. This combination, i.e. DWR and ZDR, can reduce the ambiguity in D_m retrievals caused by the variable aspect ratio AR of ice particles. While we found some influence of AR on D_m retrievals in the region between both radar instruments and at high elevation angles (e.g. 30°), ZDR from POLDIRAD was very helpful to improve D_m retrievals above the Ka-band cloud radar, or in the areas between both systems where the elevation angles of both radars are low. In these regions, ZDR measurements are essential to reduce the uncertainty in D_m retrieval from DWR

715   measurements of horizontally aligned ice oblates.

     The current version of the ice microphysics retrieval scheme considers only dry ice particles. In future studies, this methodology will be extended to include wet particles as well. In this way, we aim for a better understanding of microphysical processes of ice growth, such as aggregation or riming, to improve their representation in future weather and climate models.
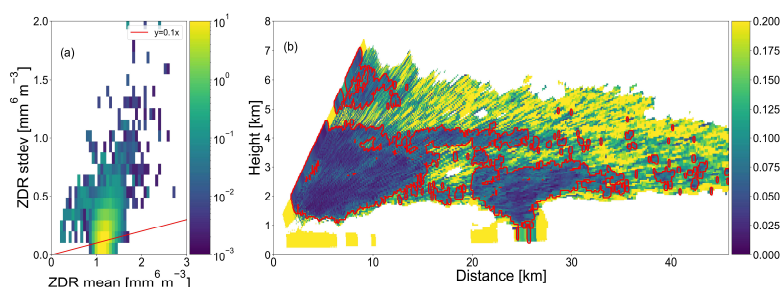
Appendix A: Radar measurements error assessment
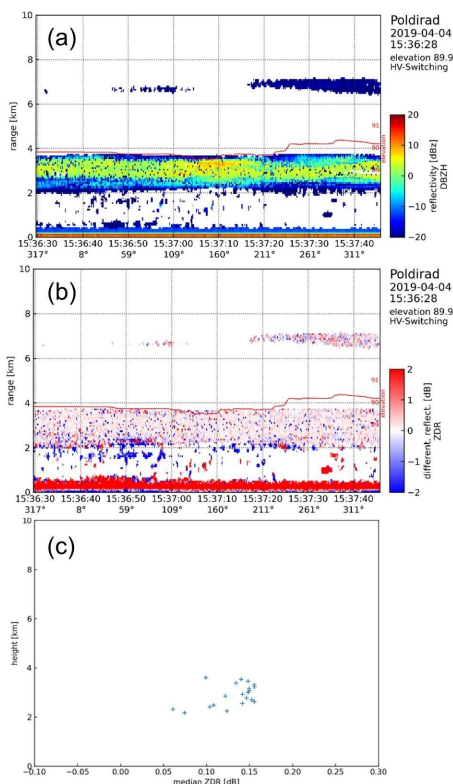
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Figure A1: POLDIRAD (a) Z_e, and (b) ZDR measurements for different times and azimuth angles of a liquid cloud layer with a vertical pointing antenna on 04 April 2019. Panel (c) shows the offset of the averaged ZDR for the range where the liquid layer was detected.


725 **Figure A2:** (a) the local standard deviation of ZDR is plotted as a function the local mean of ZDR. (b) the ratio a = ZDR_{stdev} /ZDR_{mean} can be used to filter out noisy ZDR measurements. In the red encircled areas (a < 0.1), the retrieval results are considered to be reliable enough to be aggregated into statistical results.

Appendix B: Development of an ice mask

For the ice mask implementation, variables from both radars, i.e. the LDR from MIRA-35 as well as the ZDR and ρHV
730 from POLDIRAD, were used. These variables are known to have distinct polarimetric signatures when a ML is present. The mask was applied to each vertical profile of the common grid for every pair of RHI scans. Below 4 km a ML is detected for the following condition: MIRA-35 LDR is in the range –22 dB ≤ LDR ≤ –15 dB and POLDIRAD ρHV as well as ZDR are in the range 0.75 ≤ ρHV ≤ 0.95 and 1.5 dB ≤ ZDR ≤ 2.5 dB respectively. As we focus merely on stratiform snowfall precipitation

cases and as we assume that riming or melting ice is unlikely to occur, all hydrometeors above 4 km (height above MSL)

735 and/or above ML were accounted dry. When the criteria were not met, the isotherm of 0 ºC was used as an auxiliary information for ice above that height. The temperature data were obtained from the Oberschleißheim sounding station (about 13 km north of Munich), source: Deutscher Wetterdienst, data provided by University of Wyoming; http://weather.uwyo.edu/upperair/sounding.html, last access: 10 June 2021). Although the thresholds used in the ice mask were evaluated in precipitation cases where a ML was observed, the investigation of more precipitation cases to obtain more precise

740 thresholds is needed. The necessity of sharpening the ice mask's thresholds is highlighted from Fig. B1 where an example of ZDR observations during a thunderstorm observed over Munich on 7th July 2019 is presented. Figure B1a shows ZDR without the application of any noise filters (described in Sect. 3.1), while in Fig. B1b the filtered and masked ZDR is plotted. Figure B1c presents the origin of the masked ZDR values. On 7th July 2019 at 08:22 UTC a melting layer was observed at 3 km and thus, ZDR was masked for ice hydrometeors at that height. However, the greater part of the cloud cross-section is masked

745 using the 0 ºC isotherm revealing the need for more precise ice thresholds with evaluating more case studies with mixed-phase cloud cross-sections. In the current study, only few ice hydrometeors were detected above the 0 ºC isotherm, making the sharpening of ice mask's thresholds not so crucial.
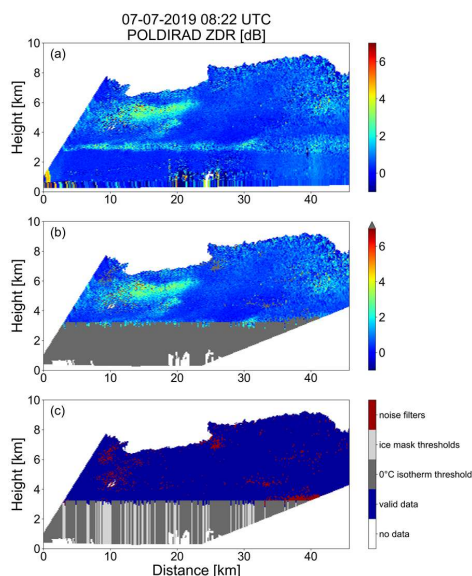
750 **Figure B1:** (a) Unfiltered POLDIRAD ZDR measurements from 7th July 2019 at 08:22 UTC. (b) Noise filtered and ice masked values of POLDIRAD ZDR plotted with grey color. (c) Different origin of filtered and masked values.

Appendix C: Estimation of minimum retrievable D_m

For sensitivity purposes regarding DWR measurements we had to consider a minimum D_m in our simulations. For this reason, we assumed a minimum value of DWR = 0.1 dB that can be observed by the two radars. The minimum retrievable D_m

755 depends not only on the viewing geometry of the two radars but also on the AR and the $m(D_{max})$ used for the calculation of the ice spheroids density. In Fig. C1 examples of the minimum retrievable D_m for different radar geometries and $m(D_{max})$ are presented. For this plot the aggregates $m(D_{max})$ is used for red and dark red line plots. When the two radar beams are both simulated to be emitted horizontally the horiz-horiz definition is used, while when C-band beam is simulated be emitted horizontally and Ka-band towards zenith the horiz-vert label is used in the legend. As all ice spheroids are assumed to be

760 aligned to the horizontal plane with small oscillations of up to 20° out of this plane, the minimum retrievable D_m is, in general,

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smaller when the radar beams are passing through the ice spheroids from the side. Assuming C-band beam emitted horizontally and for ice particles with the same size, Mie effects can be stronger for Ka-band beam when it penetrates the particles from the side (horiz-horiz geometry) rather than from below (horiz-vert geometry), as the beam path is longer inside the particle. For horiz-horiz geometry, $Z_{e,Ka}$ values are lower and thus, DWR is higher than for horiz-vert geometry for same particle size.

765 Therefore, the lowest minimum retrievable D_m is smaller in horiz-horiz than in horiz-vert geometry. From the comparison of red (aggregates m(D_{max})) and blue (BF95 m(D_{max})) color line plots, in which the radar beams are simulated to be emitted horizontally (C-band) and vertically (Ka-band), the minimum retrievable D_m for aggregates m(D_{max}) is larger compared to BF95, due to the higher effective density of aggregates. The less dense the particles are, the smaller the D_m will be for the minimum DWR threshold of 0.1 dB. For the same geometry (C-band emitted horizontally and Ka-band emitted vertically) and

770 both mass-size relations, the more aspherical the particles the larger the minimum retrievable D_m due to the larger cross-section of the horizontally aligned spheroids for the Ka-band beam.
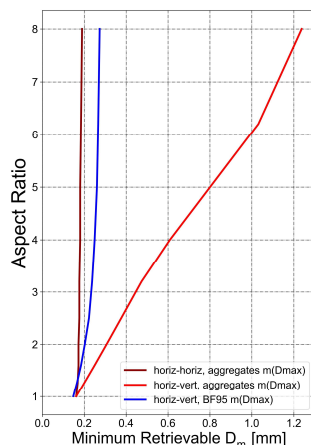

Figure C1: Minimum possible retrieved D_m for aggregates m(D_{max}) when C-band and Ka-band beam are emitted horizontally (dark red).
775 With red and blue color, the minimum possible retrieved D_m for aggregates and BF95 m(D_{max}) when C-band beam is emitted horizontally and Ka-band is emitted towards zenith is plotted.

Data availability

Hersbach et al. (2018) was downloaded from the Copernicus Climate Change Service (C3S) Climate Data Store. DOI: 10.24381/cds.bd0915c6. The author did not download the data to distribute them. The results contain modified Copernicus
780 Climate Change Service information 2020. Neither the European Commission nor ECMWF is responsible for any use that may be made of the Copernicus information or data it contains. Radar data from POLDIRAD weather radar from DLR as well as MIRA-35 cloud radar from LMU are available upon request to the authors.

Author contribution

In the framework of the IcePolCKa project ET, FE, MH and GK performed radar measurements during precipitation events.
785 ET developed the method used in this work and wrote the final paper under the consultation of FE. SG and TZ contributed to this work with productive discussions during the development of the ice microphysics retrieval. All authors contributed helpful comments to the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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