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How Does Riming Affect Dual-Polarization Radar Observations and Snowflake Shape?

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Abstract As an ice particle grows by riming its shape is expected to change, resulting in a more spherical particle at the later stages of riming. This conceptual model is at the core of the current ice microphysical schemes and used for dual-polarization radar observation based classification of hydrometeors. A quantitative relation between riming and shapes of snowflake aggregates, however, has not been established yet. This study aims to derive this relation by using surface-based precipitation and coinciding dual-polarization radar observations. The observations were collected during four winter seasons, 49 snowstorms, at University of Helsinki measurement station in Hyytiälä, Finland. Results show that relation between the differential reflectivity and reflectivity-weighted rime mass fraction is not monotonic and depends on reflectivity-weighted mean diameter. This behavior can be explained by the opposing effects of riming on dual-polarization radar observations. Riming increases particle bulk density, which leads to more pronounced dual-polarization radar signatures. As riming progresses the aspect ratio of snowflake increases slowly until the rime mass fraction value reaches a certainty value after which the aspect ratio increases more rapidly. Finally, utilization of $Z_d$, $Z_{dr}$, and $K_{dp}$ for inferring riming fraction is analyzed.

1. Introduction

Snow plays an important role in global precipitation (Field & Heymsfield, 2015). Snow growth processes such as vapor deposition, aggregation, and riming are responsible for precipitation formation and control physical properties of ice particles. It was shown that riming might be responsible for 40% to 100% of snow mass accumulation (Harimaya & Sato, 1989; Mitchell et al., 1990; Moisseev et al., 2017). In addition, Grazioli et al. (2015) have advocated that precipitation intensity and degree of riming are positively correlated. Furthermore, riming is one of the primary precipitation processes that may be affected by anthropogenic emissions (Jackson et al., 2012). For example, Borys et al. (2003) showed that increased anthropogenic aerosol concentration could inhibit riming and result in lower snowfall rates. Similar results have also been reported in climate simulations, but with more sophisticated climate implications (Lohmann, 2004).

Traditionally, in cloud and weather model microphysical schemes, riming is represented as an autoconversion from unrimed snow to graupel (e.g., Ferrier, 1994). This transition between different ice types is abrupt and not very physical (Morrison & Grabowski, 2008). In the recently proposed predicted particle properties (P3) microphysical scheme (Morrison & Grabowski, 2008; Morrison & Milbrandt, 2015) the rime mass fraction is directly predicted and ice particle properties vary continuously. Since the ice particle growth rate depends on particle shape, the evolution of particle aspect ratio needs to be taken into account (Jensen & Harrington, 2015). Jensen et al. (2017) have modeled the evolution of ice crystal shape during riming and compared it to wind tunnel measurements.

Knowledge of ice particle shapes is also of importance for dual-polarization radar data based particle identification methods (e.g., Chandrasekar et al., 2013; Straka et al., 2000; Thompson et al., 2014; Vivekanandan et al., 1999). Using these methods, dual-polarization radar echoes are separated into categories, for example, caused by snowflakes, ice crystals, and graupel. Better understanding of the impact of riming on dual-polarization radar variables, therefore, could lead to improved classification schemes.

Optical disdrometers and particle imagers, aircraft, or ground based, could be used to ascertain particle shapes (Garrett et al., 2015). However, given that characteristics of the three-dimensional ice particle shape are derived from two-dimensional images, there are large uncertainties in the retrieved aspect ratios (Jiang et al., 2017).
In this study, we are using a combination of ground-based snowfall and dual-polarization radar measurements to quantify a connection between snowflake shape and rime mass fraction. The main focus is not on the shapes of pristine ice crystals but on aspect ratios of aggregated snowflakes. Given a rather unique data set used in this research, to our knowledge, no other study addressing this topic has been published yet. In this paper, one basic question is answered. How do the dual-polarized radar variables and aspect ratio of snowflakes depend on the rime mass fraction? Results of this analysis will help to advance our understanding on riming-driven evolution of ice particles, parameterization of riming in numerical model, and dual-polarization radar-based retrievals.

2. Measurements

2.1. Surface Precipitation Measurements

The data used in this study were collected at University of Helsinki Station for Measuring Ecosystem-Atmosphere Relations (SMEAR II) located in Hyytiälä (61.845°N, 24.287°E). Liquid water path (LWP) is retrieved from microwave radiometer (MWR) measurements (Cadeddu et al., 2013). Microphysical properties of falling snowflakes were recorded by a combination of National Aeronautics and Space Administration (NASA) Particle Imaging Package (PIP) (Newman et al., 2009; Tiira et al., 2016) and two OTT Pluvio² weighing gauges. These instruments were provided by NASA Global Precipitation Measurement (GPM) ground validation program.

The PIP is a new generation of Snowflake Video Imager (Newman et al., 2009) consisting of a lamp and a charge-coupled full frame camera. The field of view of this camera is 48 × 64 mm with pixel size of 0.1 × 0.1 mm. The lens focus for the camera is set at 1.3 m, which minimizes wind impact on sample volume induced by instrument housing (Newman et al., 2009). Basic PIP products include particle size distribution (PSD), fall velocity, and various particle geometry descriptors. The PSD is recorded in diameter bins starting from 0.2 mm and extending to 26 mm with the resolution of 0.2 mm.

In addition to PIP, two OTT Pluvio² weighing gauges are used in this study. One with an orifice of 200 cm² is referred as OTT Pluvio² 200 and is located inside the Double-Fence Intercomparison Reference wind protection, the other, 20 m away from the DFIR, is OTT Pluvio² 400 with 400 cm² orifice (Petäjä et al., 2016; Tiira et al., 2016). Every 5 min, the integrated PIP and gauge observations are used to retrieve mass-size relations (von Lerber et al., 2017). Typically, the OTT Pluvio² 200 measurements are used for this retrieval; only in few cases where this gauge was not operational, data from OTT Pluvio² 400 is utilized.

To characterize the mean particle size, in addition to the standard PSD parameters, the reflectivity weighted mean diameter is computed as

\[
D_{Ze} = \frac{\int_{D_{min}}^{D_{max}} D^2 m_{ob}(D) N(D) dD}{\int_{D_{min}}^{D_{max}} m_{ob}(D) N(D) dD}
\]

(1)

where \(D_{max}\) and \(D_{min}\) are maximum and minimum recorded particle sizes, respectively, \(m_{ob}(D)\) and \(N(D)\) are average mass for a given particle size and measured snowflake size distribution based on the technique proposed by von Lerber et al. (2017), respectively. Similar to Falconi et al. (2018), the particle size here is defined as the observed maximum particle dimension \(D_{max,ob}\) derived from PIP only. In the study by von Lerber et al. (2017), two particle dimensions are introduced, the observed maximum particle dimension, \(D_{max,ob}\) and true maximum dimension, \(D_{max, true}\). The latter one is the modified particle size tuned to match retrieved and observed precipitation accumulations. The \(D_{max, true}\) plays a role of a tuning parameter and does not necessary represent a snowflake size. Falconi et al. (2018) have shown that by using the derived particle masses and observed maximum particle dimension a good match between observed and computed equivalent reflectivity factors can be achieved. Here and hereafter \(D\) represents observed particle maximum dimension. It should be noted that \(D_{Ze}\) is derived using Rayleigh scattering approximation, which is a rather good approximation for C-band radar observations.

2.2. Radar Data

To retrieve snowflake aspect ratios in addition to the surface precipitation observations, data from Finnish Meteorological Institute (FMI) C-band dual-polarization weather radar is utilized. The radar operates in the simultaneous transmission and receiving mode (Doviak et al., 2000). The FMI radar is located in Ikaalinen, around 64 km west from the SMEAR II station. The radar performs range height indicator scan every
15 min and low level, elevation angle 0.3° (around 600 m above Hyytiälä site), plan position indicator scans every 5 min. From the plan position indicator measurements, equivalent reflectivity factor, \( Z_e \), and differential reflectivity, \( Z_{dr} \), above the site are derived by averaging data from the seven closest range gates and three radar beams. The range resolution is 500 m, and the azimuth resolution is 1°.

The calibration of the differential reflectivity measurements was performed using a combination of vertically pointing precipitation scans, Sun monitoring (Huuskonen et al., 2016), and analysis of \( Z_e-Z_{dr} \) light rainfall data (Bringi & Chandrasekar, 2001). It was determined that during 4 years, the transmitter powers in the two polarization channels stayed balanced within 0.1 dB. Therefore, the \( Z_{dr} \) calibration can be performed by adjusting sun measurements by a constant factor representing transmitter power difference. This approach provides continuous \( Z_{dr} \) calibration, even in absence of suitable rainfall or vertically pointing precipitation scans.

2.3. Data Selection

The measurements started during the Biogenic Aerosols Effects on Clouds and Climate (BAECC) campaign (Petäjä et al., 2016) and extended through the winter 2016/2017. During the period, more than 60 snowstorms were observed. Here a snowstorm is defined as a precipitation event with liquid water equivalent accumulation of 2 mm or more and surface temperature below 0 °C. Since our interest is on studying impact of riming on shapes of snowflakes and not of pristine crystals, only events when surface temperatures were higher than −10 °C were selected. This reduces the number of events to 49 snowstorms. In Figure 1, distributions of the air temperatures recorded during the events are given. The distributions are given for three particle size categories used in this study. Each observation represents 5 min. As can be seen, most precipitation cases fall in the temperature range between −5 °C and 0 °C. The list of events and corresponding environmental conditions is given in the supporting information.

3. Methods

3.1. Rime Mass Fraction Retrieval

During riming snowflakes accrete ice by collecting supercooled water droplets. According to the conceptual model of Heymsfield (1982), at the first stage of riming, the accreted ice fills in the unoccupied space in a snowflake. During this stage, the particle mass is increasing, while the maximum dimension remains constant. The fill-in stage continues until a quasi-spherical shape is reached and the maximum dimension begins to increase. This conceptual model is at the core of the P3 microphysical scheme proposed by Morrison and Grabowski (2008) and further developed by Morrison and Milbrandt (2015). In this scheme, the rime mass fraction is a prognostic variable. The rime mass fraction is defined as the ratio of accreted ice mass to the total snowflake mass and can be written as

\[
FR = 1 - \frac{m_{ur}(D)}{m_{ob}(D)}
\]

where \( m_{ur}(D) \) denotes mass of initial unrimed snowflakes for a given particle size. Erfani and Mitchell (2017) have shown that the exponent of a mass-size relation expressed in the power law form does not change with riming, at least until a graupel particle is formed. This implies that FR is constant with \( D \) and the mass-size relation can be written as

\[
m(D) = \frac{\alpha}{1 - FR} D^\beta
\]

where \( \alpha \) and \( \beta \) are parameters of unrimed snowflake \( m(D) \) relation.

Moisseev et al. (2017) have followed this approach and have derived the mass-size relation for unrimed snowflakes using the ensemble mean snow density retrieved by Tiira et al. (2016). Using data collected during BAECC and winter 2014/2015, they have found that the relation

\[
m_{ur}(D) = 0.0053D^{2.05}
\]
Figure 2. Scatterplot for retrieved snow mass-size relation during Biogenic Aerosols Effects on Clouds and Climate. LWP = liquid water path.

Every 5 min, if enough snowflake have been recorded, a mean particle mass is retrieved for each size bin. To retrieve the rime mass fraction from this data, we need to find FR that minimizes the difference between the mass-size relation given in the equation (3) and retrieved particle masses. This can be done using a number of methods and fitting procedures; the main difference between them is the weights assigned to mass measurements of particles of different sizes. Since this study is based on analysis of radar data to retrieve ice particle aspect ratios, the weights should correspond to the particle contribution to the radar reflectivity. Following this logic the rime mass fraction is computed as follows:

$$FR = 1 - \left( \frac{\int_{D_{\text{min},5}}^{D_{\text{max},5}} m_{\text{tot}}(D) N(D) \, dD}{\int_{D_{\text{min},5}}^{D_{\text{max},5}} m_{\text{ob}}(D) N(D) \, dD} \right)^{\frac{1}{2}}$$

(5)

where $D_{\text{max},5}$ and $D_{\text{min},5}$ are corresponding maximum and minimum recorded particle sizes in 5 min respectively. It should be noted that (2) and (5) are identical in cases where exponents of $D_{\text{max}}$ and $D_{\text{min}}$ are the same. In reality, the exponent of $m_{\text{tot}}(D)$ may be different. To derive FR in such a case, we need to fit a power law function to $m_{\text{ob}}(D)$ that has the same exponent as $m_{\text{tot}}(D)$. There are several ways to do such a fit, given that we are interested in comparing ground-based and radar observations, the fitting is done by giving more weight to particles that contribute the most to the radar observations, as shown in (5). The comparison of the computed rime mass fraction values to the ones reported by Moisseev et al. (2017) shows a rather good agreement. Figure 3 presents the comparison between equivalent LWP (ELWP) computed from FR and

In this study, instead of ensemble mean densities we use retrieved snowflake masses. Additionally, the particle dimension metrics are slightly different. In Tiira et al. (2016) the area equivalent diameter is computed to the maximum particle dimension using a single conversion factor, while von Lerber et al. (2017) derive the particle maximum dimension from PIP observations. Therefore, the applicability of the unrimed mass-size relation needs to be verified. To verify the applicability of relation (4), microwave radiometer observations of LWP and retrieved snowflake mass collected during BAECC are used. The consideration is that riming may not take place under low liquid water environment, thus LWP provides a more solid means to select unrimed cases. Given the situation that retrieved snowflake mass swings along the expected power law relation, the retrieved mass for each size bin in every 5 min is fitted by a power law with the power of 2.05 for comparison with the derived relation in Moisseev et al. (2017). As shown in Figure 2, for a given $D$ snowflake mass can vary by a factor of 10, which yields FR values ranging from 0 to 0.9 according to (2). We set 20 g/m$^2$ as the upper limit of LWP for unrimed cases, most of which in fact are located in the lower part of the scatter plot. With a fixed power, the fitted $m_{\text{ur}}(D)$ prefactor is 0.0052 which is very close to the value in (2). Lifting the threshold to 30 g/m$^2$ did not change the fitted prefactor much. Given that the relation (4) is very close to the fitted relation in Figure 2, (4) is adopted as mass-size relation for unrimed snow in this paper.

The FR retrieval method is similar to the one proposed by Moisseev et al. (2017). The main difference between this FR retrieval method and the one proposed by Moisseev et al. (2017) is the used data. Von Lerber et al. (2017) have used hydrodynamic equations linking particle fall velocity and mass, as proposed by Böhm (1989) and further extended in (Mitchell & Heymsfield, 2005). The snowflake masses are retrieved from PIP observations of particle fall velocity and geometrical properties, such as the maximum dimension and area ratio. Because the geometrical properties are taken from side images, while particle dimensions as projected to the airflow are needed, a correction factor is introduced (von Lerber et al., 2017). This correction factor is computed by matching PIP based and gauge snowfall accumulations. This step is done on event by event basis.

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LWP measured by the MWR, as well as the cumulative distribution of LWP. The ELWP is defined as (Moisseev et al., 2017)

\[
\text{ELWP} \approx \frac{4\pi}{53} \frac{\text{FR}}{1-\text{FR}} \approx 67.5 \frac{\text{FR}}{1-\text{FR}} \text{ (g/m}^2\text{)}
\]  

(6)

The presented comparison uses only cases recorded during BAECC, because during this time period an MWR was operating at the site. The correlation coefficient between the ELWP and LWP is 0.75. For most cases the ELWP is less than half of LWP, which could be explained by the assumptions used to convert FR to ELWP and differences between particle trajectory and MWR vertical column (Moisseev et al., 2017).

Using linear fitting for LWP-ELWP, the slope is 0.45 with the root-mean-square error of 58 g/m².

3.2. Snowflake Aspect Ratio Retrieval

To retrieve ice particle aspect ratios, ARs, surface-based observations of \(m(D)\) and PSD are combined with the C-band radar differential reflectivity measurements. The observations are matched by finding a time lag that maximize the cross correlation between radar observed equivalent reflectivity factors measured by the radar and computed from surface observations using Rayleigh approximation. On average this time lag is about 5–10 min.

To compute the differential reflectivity, \(Z_{dr}\), from surface observations, ice particles are modeled as oblate spheroids (Matrosov, Heymsfield, & Wang, 2005). The spheroids are preferentially oriented horizontally, with the canting angles sampled from Gaussian distribution with an assumption of certain standard deviation \(\sigma_\theta\) and azimuth angles are sampled from uniform distribution. The scattering properties are computed using T-matrix method (Leinonen, 2014; Mishchenko & Travis, 1994; Wieland et al., 1997). The refractive index of ice particles is estimated using the Maxwell Garnett effective media approximation (Sihvola, 1999). Given that the surface observations provide particle masses and PSD as a function of maximum dimension, and the particle volume is not defined, the aspect ratios do not only define shape but also determine density and refractive index of snowflakes. For the retrieval, the \(Z_{dr}\) values were computed using AR values ranging from 0.2 to 1 with a step of 0.025. Using these computations and \(Z_{dr}\) observations, the aspect ratios are defined as those that minimize the difference between the observed and computed \(Z_{dr}\) values. The block diagram of the AR retrieval is summarized in Figure 4. Given that AR has a limited impact on the radar reflectivity factor, cases where the difference between the simulated and observed reflectivity values exceeds 5 dB are not used in this study. During the analysis we have noticed that especially during shallow precipitation events the agreement between ground and radar observations may be poor. Most probably this is caused by non-uniform beam filling. To limit this effect, the 5 dB threshold was introduced. No significant changes in the results were observed if the threshold value is reduced.

The uncertainty of the aspect ratio estimate depends on uncertainty of \(\sigma_\theta, Z_{dr}, m(D)\), and PSD observations. The PSD estimate uncertainties are rather small given that we only consider observations where on average more than 10³ ice particles were recorded (von Lerber et al., 2017). The \(m(D)\) estimate error is more difficult to quantify. It depends on uncertainties of particle velocity measurements, which are relatively small, and uncertainties in relations connecting particle fall velocity and mass. Garrett and Yuter (2014) observed that fall velocities of ice particles are strongly influenced by turbulence and therefore a connection between particle mass and fall velocity may be ill defined. Our measurement site is sheltered and wind velocities at the site are small, typically less than 2 m/s. Therefore, the impact of air motion is rather small.

Figure 3. Scatterplot for LWP versus ELWP (blue) and accumulated fraction of LWP (orange) during BAECC. LWP = liquid water path; EWLP = equivalent LWP; BAECC = Biogenic Aerosols Effects on Clouds and Climate; RMSE = root-mean-square error.

Figure 4. Block diagram for aspect ratio retrieval procedure.
In order to verify the retrieved particle masses a consistency check against other observations was performed (Petäjä et al., 2016). For example, the derived $m(D)$ was used to compute the ensemble mean density, which was compared to the estimates of Tiira et al. (2016). It was found that they agree rather well. The idea behind this consistency check is to use observations or retrievals that either performed using different instruments or use different retrieval assumptions.

It is expected that $Z_{dr}$ calibration bias is in the order of 0.1–0.2 dB (Bringi & Chandrasekar, 2001; Doviak et al., 2000). For smaller denser snowflakes change in AR would result in a change in $Z_{dr}$ that exceeds 0.2 dB. For larger low-density ice particles, the impact of AR on $Z_{dr}$ is less pronounced. To study this effect an idealized simulation is carried out. In this simulation, PSD is assumed to be exponential and $\sigma_\theta$ is 10°. In Figure 5a the results of this simulation are shown. It can be seen that for a given $D_{Z_{dr}}$ and $\sigma_\theta$, AR and FR have competing impacts on $Z_{dr}$. The $Z_{dr}$ values increase as riming progresses, and this increase is larger for particles with smaller $D_{Z_{dr}}$ and AR. On the contrary, the increase of AR makes snowflakes more spherical and reduces $Z_{dr}$. In general, the AR impact seems to change $Z_{dr}$ more significantly than FR. For particles with $D_{Z_{dr}} = 2$ mm, AR = 0.4, and FR = 0, the increase of AR from 0.4 to 0.6 decreases $Z_{dr}$ by about 0.3 dB, while increase in FR by 0.2 raises $Z_{dr}$ by about 0.1 dB. Thus, altering particle shape is the dominate factor of changing $Z_{dr}$ for a fixed $\sigma_\theta$. For a given $Z_{dr}$ uncertainty of 0.1–0.2 dB, expected error in the retrieved AR would be 0.1–0.2 for cases where $D_{Z_{dr}}$ is equal or larger than 5 mm. Due to the large uncertainty in retrieving AR for larger particles, we do not apply this retrieval technique to particles with $D_{Z_{dr}} > 3$ mm.

The final contributor to the AR estimate uncertainty is the particle orientation assumption expressed in terms of $\sigma_\theta$. Early studies (e.g., Kajikawa, 1976; Klett, 1995; Zikmunda & Vali, 1972) found that ice particle canting angle ranges from 5° to 25°. Video camera records show that the median orientation is between 35° and 39° (Garrett et al., 2015), which indicates $\sigma_\theta$ might be up to 30°–40°. Nevertheless, polarized radar measurements seem to show smaller $\sigma_\theta$ in some case studies. With the combination of horizontal-vertical polarization and slant polarization radar configurations, Matrosov, Reinking, and Djalalova (2005) found that $\sigma_\theta$ value lies in an interval from 3° to 15° for lightly precipitating ice clouds. The standard deviation of canting angles is also reported to be 2°–23° under the ambient temperature between −20 °C and −10 °C in a more recent study (Melnikov, 2017). Based on reported $\sigma_\theta$ values, $Z_{dr}$ is calculated with different assumptions on $\sigma_\theta$, that is, 10°, 20°, and 30°. As shown in Figure 5b, $Z_{dr}$ decreases if $\sigma_\theta$ increases. For a given $Z_{dr}$, the uncertainty of retrieved AR due to $\sigma_\theta$ assumption is about 0.15 or less. This uncertainty seems to be independent of the value of rime mass fraction. For a given AR, the decrease of $\sigma_\theta$ increases $Z_{dr}$. More specifically, for particles

![Figure 5](https://example.com/figure5.png)

**Figure 5.** (a) Simulated $Z_{dr}$-FR relations for AR values of 0.4, 0.6, and 0.8, assuming fixed $\sigma_\theta$ of 10°. (b) The $Z_{dr}$-FR relations for $\sigma_\theta$ of 10°, 20°, and 30° and two FR values of 0 and 0.6. In (b) all the curves were computed assuming $D_{Z_{dr}} = 2$ mm. The solid, dashed, and dotted lines correspond to $\sigma_\theta$ of 10°, 20°, and 30°, respectively. AR = aspect ratio; PIP = Particle Imaging Package.
with $D_{ze} = 2 \text{ mm}$ and $\text{FR} = 0$ the rise of AR from 0.4 to 0.6 leads to 0.3 dB decrease of $Z_{dr}$ (Figure 5a), while when $\sigma_{\theta}$ increases from 10° to 30° $Z_{dr}$ decreases by around 0.25 dB, which indicates that the assumption of $\sigma_{\theta}$ plays an important role.

4. Results

4.1. $Z_{dr}$-FR Relation

As the first step of the analysis, dependence of $Z_{dr}$ on FR is investigated. It is generally expected that riming should result in the reduction of $Z_{dr}$ (see, e.g., Giangrande et al., 2016; Ryzhkov et al., 2017). Moisseev et al. (2017) have observed that this may not always be the case, and $Z_{dr}$ of larger particles may not react as much to riming as smaller crystals. In Figure 6 the $Z_{dr}$-FR scatterplots and boxplots are presented.

The analysis of $Z_{dr}$-FR dependence is carried out for three $D_{ze}$ ranges. For the two smaller particle categories, the $Z_{dr}$ does not change much until FR reaches 0.45–0.55. After this value $Z_{dr}$ decreases rather rapidly to 0. This two-stage behavior presents indications on the competing effects of riming on the dual-polarization radar observations, that is, riming changes both shape and density of ice particles. As expected, the drastic drop of $Z_{dr}$ in the second stage is dominated by the increase of AR. In the first stage, $Z_{dr}$ responses to FR less sensitively, indicating that riming has much less impact on snowflake shape. For the largest particle category $Z_{dr}$ does not react much to FR. This could possibly be explained by the density of ice particles in this size range. These particles are low-density aggregates and their dual-polarization radar signatures are rather weak. However, despite weaker $Z_{dr}$ signatures for larger particle categories, the fact that $Z_{dr}$ decreases or stays more or less constant while FR increases, indicating that even larger snowflake aggregates are becoming more spherical during riming.

We should note that this interpretation of the $Z_{dr}$ observations assumes that $\sigma_{\theta}$ does not depend on riming. Garrett et al. (2015) found that riming tends to lower $\sigma_{\theta}$ but this dependence is weak, which means that the decrease of $\sigma_{\theta}$ due to riming could increase $Z_{dr}$ as well. Since there is very little information on how riming affects orientation of ice particles and measurements of particle orientations are rather uncertain, a constant $\sigma_{\theta}$ is assumed for all FR values. The retrieval of AR is performed for different values of $\sigma_{\theta}$ and relative importance of AR and $\sigma_{\theta}$ can be inferred by comparing AR values computed using different $\sigma_{\theta}$.

4.2. AR-FR Relation

Figure 7 shows AR-FR scatterplots and boxplots. As expected from the discussion in the previous section, AR increases after FR reaches 0.5 for particles with $D_{ze} \leq 2 \text{ mm}$ for all assumed $\sigma_{\theta}$ values. The mean retrieved AR decreases with the increase of $\sigma_{\theta}$ and the difference between AR values retrieved assuming $\sigma_{\theta}$ of 10° and 30° is around 0.15, which agrees with the simulation in Figure 5b rather well. One interesting difference with previous studies is that the averaged AR seems to be lower than reported 0.6 (Garrett et al., 2015; Korolev & Isaac,
Though it is possible to adjust \( \sigma_\theta \) to 0° to pull the averaged AR to be closer to 0.6, this is obviously unrealistic. As demonstrated in theoretical simulation by Jiang et al. (2017) and in observational study by Matrosov et al. (2017), the retrieved AR using single video camera can be overestimated. Therefore, the commonly adopted AR parameterization of 0.6 needs to be used more carefully. Given our lack of knowledge on the appropriate \( \sigma_\theta \) values, the arising uncertainty needs to be considered. The video camera study (Garrett et al., 2015) shows that the dependence of ice particle orientation on riming is weak, however, the orientation distribution is rather broad. As shown in Figure 7a3 and 7b3, under the assumption of \( \sigma_\theta = 30° \) the averaged retrieved AR falls below 0.4, which seems to be already too small if compared to the currently expected value of 0.6. Thus, we did not perform retrievals using higher \( \sigma_\theta \). Given the large uncertainty in retrieving AR from the \( Z_d \) observations for cases where \( D_{Z_d} > 3 \) mm, only retrieval results for the two smaller particle size categories are presented.

For small particles, AR shows a rather weak growth, while FR < 0.5, and it rapidly increases after FR exceeds 0.5. The very slow upward trend indicates that AR has very limited change with the increase of FR before FR

<table>
<thead>
<tr>
<th>( \sigma_\theta )</th>
<th>( \sigma_\theta = 10° )</th>
<th>( \sigma_\theta = 20° )</th>
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<td>0.5</td>
<td>0.77</td>
<td>2.8</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.15</td>
<td>0.16</td>
<td>0.18</td>
<td>0.15</td>
<td>0.15</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Note. RMSE = root-mean-square error.
reaches approximately 0.5. As explained by Moisseev et al. (2017), at the fill-in stage riming fills in unoccupied space inside the snow particle and has very limited impact on particle shape but gains particle mass. The slow increase of AR when FR rises from 0 to 0.5 supports this hypothesis. The rapid increase of AR when FR > 0.5 implies that at this riming stage snowflake shape begins to change. The AR values for particles with 2 mm < DZe ≤ 3 mm also rise as the FR increases. But this change is not as same as that for smaller particles. The rapid rise of AR when FR > 0.5 is still noticeable, however, despite a more linear relation between AR and FR. Another interesting finding is that unrimed AR (FR = 0) seems to be smaller for larger particles than for smaller. It may indicate that larger aggregates have smaller AR values.

Given the need to parameterize the evolution of AR during riming, values for AR versus FR are fitted using the following equation:

\[
AR = c_0 + c_1 FR + c_2 FR^2
\]  

(7)

The least squares fitting is applied to values in different particle size ranges. Table 1 presents the fitted parameters as well as the corresponding root-mean-square error under different assumptions on σθ.

### 4.3. From Radar Variables to FR

In hydrometeor classification schemes (e.g., Barthazy et al., 2001; Chandrasekar et al., 2013; Lim et al., 2005; Straka et al., 2000; Thompson et al., 2014) that are based on dual-polarization radar data, such variables as Ze and Zdr are used, for example, to identify signatures of snow aggregates, crystals, and graupel. To investigate whether Ze and Zdr observations can be used to diagnose the rime mass fraction, the scatterplot of Zdr versus Ze for different values of FR is shown in Figure 8. The data are subdivided into two regions, the small particle region where DZe ≤ 2 mm, and the large particle region.

For the small snowflakes, Ze varies between −5 and 15 dBZ and Zdr ranges between 0 and 1 dB. It can be observed that there is no a well-defined trend describing Zdr dependence on FR for Zdr > 0.15 dB, but heavy riming cases are characterized by Zdr values smaller than 0.2 dB. In addition, no case with FR > 0.6 exhibits high Zdr (Zdr > 0.6 dB), which could also be seen in Figure 6a. However, it is hard to quantify light to moderate riming by just relying on Ze and Zdr measurements. For cases with DZe > 2 mm, Zdr decreases with the increase of Ze. This relation is expected and has been reported before (e.g., Vivekanandan et al., 1994; Williams et al., 2015). To further investigate, how dual-polarization radar variables can be used in inferring the rime mass fraction, the Zdr-Kdp relation is investigated.

Figure 9 shows Zdr-Kdp relations grouped by observed Ze. Figure 9a shows cases where Ze ≤ 15 dBZ and Figure 9b presents cases where Ze > 15 dBZ. The larger Ze cases exhibit dependence of Zdr and Kdp on FR. It should be noted that the span of Kdp values is not very large, and it is not clear how significant is the observed trend. As can be seen in Figure 9a, the heavily rimed cases show Zdr and Kdp values that are scattered throughout the plot and do not show dependence on FR.

For cases with Ze > 15 dBZ, it is clear that low Zdr-Kdp corresponds to high FR as demarked by the black rectangle 1 and vice versa as indicated by the rectangle 2. Thus, it is highly possible that particles with Ze > 15 dBZ, Zdr < 0.15 dB, and Kdp < 0.075 deg/km are moderately or heavily rimed.
5. Conclusions

In this paper, synergy of ground-based precipitation and dual-polarization radar measurements was employed to study impact of riming on the shapes of snowflake aggregates. It was found that particle shape change follows two stages. At the first stage, where the rime mass fraction is less than 0.5, the particle shape does not change very much. As the rime mass fraction increases beyond this value, the particle aspect ratio starts to rapidly increase. Using the presented observations, parameterizations of aspect ratio relations on the rime mass fraction for two snowflake size ranges using different assumptions of canting angle distribution were derived. It appears that if the standard deviation of the canting angle distribution is assumed to be larger or equal to 30°, the retrieved particle aspect ratios would be smaller than 0.4 on average. For narrower canting angle distributions, the retrieved particle aspect ratios are about 0.5, which is closer to the value presented in literature.

The impact of riming on dual-polarization radar variables was also investigated. It was found that the differential reflectivity also exhibits the two-stage behavior as a function of the rime mass fraction. The Zdr values do not change much for particles with the rime mass fraction of less than 0.5. After this value Zdr rapidly decreases to 0. It should be noted that this behavior was only observed for two smaller particle size categories. For larger particles impact of FR on Zdr was less pronounced. In the Zdr-ZDR and Kdp-ZDR spaces, dependence of radar variables on the rime mass fraction was only observed for cases where Zdr > 15 dBZ. So it appears to be possible to diagnose riming from the dual-polarization radar observations in cases where Zdr > 15 dBZ. For lighter snowfall cases, the relation between radar variables and rime mass fraction is less obvious. The exact cause of the found response of dual-polarization radar variable on FR is not clear and warrants more future studies.
