Polarimetric Signatures above the Melting Layer in Winter Storms: An Observational and Modeling Study

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ABSTRACT

Polarimetric radar observations above the melting layer in winter storms reveal enhanced differential reflectivity $Z_{DR}$ and specific differential phase shift $K_{DP}$, collocated with reduced copolar correlation coefficient $r_{hv}$; these signatures often appear as isolated “pockets.” High-resolution RHIs and vertical profiles of polarimetric variables were analyzed for a winter storm that occurred in Oklahoma on 27 January 2009, observed with the polarimetric Weather Surveillance Radar-1988 Doppler (WSR-88D) in Norman. The $Z_{DR}$ maximum and $r_{hv}$ minimum are located within the temperature range between $-10^\circ$ and $-15^\circ$C, whereas the $K_{DP}$ maximum is located just below the $Z_{DR}$ maximum. These signatures are coincident with reflectivity factor $Z_{H}$ that increases toward the ground. A simple kinematical, one-dimensional, two-moment bulk microphysical model is developed and coupled with electromagnetic scattering calculations to explain the nature of the observed polarimetric signature. The microphysics model includes nucleation, deposition, and aggregation and considers only ice-phase hydrometeors. Vertical profiles of the polarimetric radar variables ($Z_{H}$, $Z_{DR}$, $K_{DP}$, and $r_{hv}$) were calculated using the output from the microphysical model. The base model run reproduces the general profile and magnitude of the observed $Z_{H}$ and $r_{hv}$ and the correct shape (but not magnitude) of $Z_{DR}$ and $K_{DP}$. Several sensitivity experiments were conducted to determine if the modeled signatures of all variables can match the observed ones. The model was incapable of matching both the observed magnitude and shape of all polarimetric variables, however. This implies that some processes not included in the model (such as secondary ice generation) are important in producing the signature.
1. Introduction

Accurate forecasts and quantitative estimation of winter precipitation remain a difficult problem, as the absence of adequate observations leads to significant uncertainty in diagnosing the thermodynamic state of the atmosphere. This uncertainty is compounded by the fact that slight changes in thermodynamic conditions can alter ice crystal habits, which can profoundly affect the surface precipitation rates. Although remote sensing provides information about the spatial extent of winter precipitation, conventional single-polarization radars offer little or no insight into the microphysics of the storm. This is changing, as the U.S. National Weather Service Weather Surveillance Radar-1988 Doppler (WSR-88D) network is being upgraded to have dual-polarization capabilities, which will provide operational meteorologists considerably more information regarding the microphysical properties of winter precipitation (e.g., Zrnić and Ryzhkov 1999; Straka et al. 2000; Bringi and Chandrasekar 2001; Ryzhkov et al. 2005).

Previous observational studies of winter precipitation using polarimetric radar data (Bader et al. 1987; Wolde and Vali 2001; Hogan et al. 2002; Moisseev et al. 2009; Kennedy and Rutledge 2011; Bechini et al. 2011) have identified a unique polarimetric signature located above the melting layer. Kennedy and Rutledge (2011) recently used a simple model to investigate the microphysical origins of the observed signature. The motivation for our study is twofold. First, we use polarimetric radar observations from a winter-storm case to demonstrate the repeatability of this signature. Second, we employ a much more sophisticated microphysical model coupled to electromagnetic scattering calculations in an attempt to reproduce the signature in all polarimetric radar variables. We do this in an attempt to understand what microphysical processes are involved in producing the observed signature.

The paper is organized as follows. The next section provides a brief overview of the polarimetric radar variables, with an emphasis on their application to winter stratiform precipitation, as well as a review of previous studies that investigate winter storms with polarimetry. Section 3 presents the data from an Oklahoma winter-storm case. The microphysical and electromagnetic model is described in section 4, and results are presented in section 5. The paper concludes with a summary in section 6.

2. Background

a. Polarimetric radar variables

The WSR-88D radar network is being upgraded to achieve dual polarization, adding considerable information to what is available from conventional single-polarization radar data. Along with the conventional radar reflectivity factor at horizontal polarization $Z_H$, polarimetric variables used in this study include radar reflectivity factor at vertical polarization $Z_V$, differential reflectivity $Z_{DR}$, specific differential phase shift $K_{DP}$, and copolar correlation coefficient $\rho_{hv}$. Some typically observed values of $Z_H$, $Z_{DR}$, $K_{DP}$, and $\rho_{hv}$ for snow are given in Table 1. Here, we provide a brief overview of the polarimetric variables in winter stratiform precipitation. Other sources (e.g., Doviak and Zrnić 1993; Zrnić and Ryzhkov 1999; Straka et al. 2000; Bringi and Chandrasekar 2001; Ryzhkov et al. 2005) provide more detailed information.

The following descriptions and ranges of values apply to S-band observations. Differential reflectivity is the difference between $Z_H$ and $Z_V$ (in logarithmic units) and depends on shape, orientation, density, and phase composition (which affects the dielectric constant) of hydrometeors; it is independent of hydrometeor concentration, however. Reflectivity $Z_{DR}$ is positive in rain, but the presence of ice hydrometeors decreases $Z_{DR}$ because the dielectric constant of ice is much lower than the dielectric constant of water. Thus, $Z_{DR}$ in dry snow is usually lower than $Z_{DR}$ in rain, except in drizzle or very light rain. For spherical or randomly oriented crystals, $Z_{DR}$ is equal to 0 dB; $Z_{DR}$ will increase with increasing oblateness, density, or water fraction, however. Ice particles with a pronounced oblate shape, high density, and preferential horizontal orientation can produce high $Z_{DR}$ (theoretically up to 10 dB). On the other hand, snow aggregates are larger but have very low density and more spherical shapes, producing much smaller $Z_{DR}$ (in general, $<$0.5 dB).

The copolar cross-correlation coefficient $\rho_{hv}$ is a measure of the correlation between the backscattered horizontally and vertically polarized signals from scatterers within a sampling volume. The correlation coefficient $\rho_{hv}$ is affected by the diversity of shapes, orientations, and phase compositions within a radar sampling volume. In rain, $\rho_{hv}$ is close to unity, although sometimes it decreases as a result of diversity in orientation and shape of raindrops. For spherical particles of any size, $\rho_{hv}$ is equal to unity, but it will decrease with increasing diversity in oblateness, randomness in orientations, and water content. In melting snow (or hail), $\rho_{hv}$ decreases noticeably (although still $> 0.85$) because of the mixture of water and ice.

The specific differential phase $K_{DP}$ ($\text{deg} \cdot \text{km}^{-1}$) is proportional to the range derivative of the total propagation differential phase $\Phi_{DP}$, which depends on the complex forward-scattering amplitude. The propagation differential phase $\Phi_{DP}$ represents an accumulated shift in phase between the horizontally and vertically polarized
waves along a radar radial. Propagation differential phase $\Phi_{DP}$ is independent of attenuation affects, radar miscalibration, noise bias, and partial beam blockage (Zrnić and Ryzhkov 1999). It is much more responsive to liquid than to ice particles because it depends on the dielectric constant and orientation of the medium. Therefore, $K_{DP}$ is positive in rain, whereas regions with aggregated or spherical ice produce near-zero $K_{DP}$. Enhanced $K_{DP}$ can be found in regions of high-density pristine crystals with preferential horizontal orientation. Values of $K_{DP}$ as large as 0.8° km$^{-1}$ have been observed at S band at the cloud tops in both winter and summer storms in Oklahoma (Ryzhkov and Zrnić 1998). Ryzhkov and Zrnić (1998) analyzed polarimetric signatures of snow observed during six snow events that occurred in Oklahoma. The values of $K_{DP}$ ranged from 0.01° to 0.08° km$^{-1}$ at S band in regions with snow at the lowest elevation (0.5°). Strong electric fields within clouds can cause vertical alignment of ice crystals, which can produce negative $K_{DP}$. Measurements of $K_{DP}$ at S band tend to be very noisy in dry snow (because of low radial slope of $\Phi_{DP}$), which is the biggest disadvantage of this polarimetric variable.

b. Polarimetric radar observations in winter storms

The information provided by the dual-polarization radar variables has been used in previous observational studies to investigate winter storms. Bader et al. (1987) investigated the relationship between the ice-phase microphysical structure of a stratiform cloud over England and $Z_{DR}$ using simultaneous aircraft and S-band dual-polarization radar observations. Values of $Z_{DR}$ of 3–4 dB observed at the cloud top were associated with large dendritic crystals up to 2 mm in size. Regions of enhanced $Z_{DR}$ at an average temperature level of $-7^\circ$C (or at approximately 3 km AGL) were associated with planar crystals (plates and stellar dendrites).

Wolde and Vali (2001) collected data using the University of Wyoming King Air aircraft equipped with a 3-mm-wavelength cloud radar and array probes for the detection and sizing of hydrometeors with diameters from 2 $\mu$m to several millimeters. Winter cloud types included in the sampling were altostratus, altocumulus, nimbostratus, cumulus, and stratocumulus over Wyoming. It was shown that polarimetric signatures can be useful indicators of pristine crystals growing by deposition. In addition, combinations of polarimetric variables were used to distinguish lightly rimed crystals from heavily rimmed crystals or aggregates. With polarimetric measurements, it was possible to locate and determine the relative proportions of cloud volumes where crystals were growing by deposition.

Hogan et al. (2002) investigated microphysical characteristics of warm-frontal mixed-phased clouds over England, using simultaneous aircraft and S-band radar polarimetric measurements. They observed stratiform clouds containing embedded convective regions, identified by the radar as narrow convective turrets. These turrets contained large concentrations of small crystals (near $2.5 \times 10^6$ m$^{-3}$, two orders of magnitude larger than ambient values) along with supercooled liquid droplets (including droplets with diameter of $\sim 25$ $\mu$m), and narrow updrafts of 1–2 m s$^{-1}$. Embedded convection regions had high $Z_{HI}$ and low $Z_{DR}$, suggesting nearly spherical particles that were either large in size or had high density. Immediately above the observed high-$Z_{HI}$ region, there was a maximum of ice concentration measured by the aircraft, where the temperature was $-6.1^\circ$C. At the same level, at the base of high $Z_{DR}$ (up to 4 dB), aircraft sampling showed the presence of pristine columns growing by deposition in the weak updraft ($\sim 0.4$ m s$^{-1}$).

Hogan et al. explained this by suggesting an active Hallett–Mossop ice-multiplication process (Hallett and Mossop 1974) that occurred during the riming process and produced ice splinters, which then continued to grow by deposition, resulting in high $Z_{DR}$.

Plummer et al. (2010) used simultaneous S-band polarimetric radar observations along with in situ aircraft measurements over the Mediterranean Alps, aiming to develop quantitative criteria for identifying potential inflight icing conditions. They used measurements of supercooled liquid water (SLW) and ice particles within orographic cloud systems with widespread stratiform precipitation that contained embedded convection. They utilized $Z_{HI}$, $Z_{DR}$, and $K_{DP}$, as well as their statistical difference between measurements of supercooled liquid water and ice to develop probabilistic criteria giving the likelihood of the presence of SLW as a function of the polarimetric variables.

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**Table 1. Typical values of reflectivity factor $Z_{HI}$, differential reflectivity $Z_{DR}$, cross-correlation factor $\rho_{hv}$, and specific differential phase $K_{DP}$ observed in snow (e.g., Ryzhkov and Zrnić 1998; Ryzhkov et al. 1998, 2005; Zrnić and Ryzhkov 1999).**

<table>
<thead>
<tr>
<th></th>
<th>Ice crystals</th>
<th>Dry aggregated snow</th>
<th>Wet aggregated snow</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_{HI}$ (dBZ)</td>
<td>&lt;30</td>
<td>&lt;35</td>
<td>&lt;55</td>
</tr>
<tr>
<td>$Z_{DR}$ (dB)</td>
<td>Up to 4.0</td>
<td>0.0–0.5</td>
<td>0.5–2.5</td>
</tr>
<tr>
<td>$\rho_{hv}$</td>
<td>0.9–1.0</td>
<td>0.97–1.0</td>
<td>0.90–0.97</td>
</tr>
<tr>
<td>$K_{DP}$ ($^\circ$ km$^{-1}$)</td>
<td>From $-0.5$ to 0.8</td>
<td>0.0–0.5</td>
<td>0.0–0.5</td>
</tr>
</tbody>
</table>
Moisseev et al. (2009) analyzed C-band polarimetric radar and vertically pointing Doppler radar data collected in snowfall events. In an attempt to identify the dominant snow growth mechanism (deposition, aggregation, riming, and secondary ice production), they analyzed RHI scans of $Z_H$, $Z_{DR}$, and $\rho_{hv}$ along with Doppler spectra obtained with vertically pointing antenna. In regions where deposition occurred, $Z_{DR}$ was high, $Z_H$ was low, and the mean Doppler velocity rapidly increased from 0.5 to 1 m s$^{-1}$. They noted that as aggregation takes place $Z_{DR}$ decreases and $Z_H$ increases. Mean fall velocities of ice particles larger than 1.7 m s$^{-1}$ and the presence of bimodal Doppler spectra were their criteria to indicate riming. They speculated that bimodality is caused by secondary ice production.

Kennedy and Rutledge (2011, hereinafter KR11) investigated $K_{DP}$ measurements made at S band during winter storms in northeastern Colorado. They observed local maxima in $K_{DP}$ with values in a range of $\sim$0.15–0.4°C km$^{-1}$ at the level of $\sim$15°C. To explain this signature, they performed particle-growth calculations considering only deposition in continuously water-saturated conditions, and they modeled pristine dendrites and aggregates as oblate spheroids. On the basis of their calculations, which were coupled with a microwave-scattering model, oblate ice particles with moderate bulk densities and diameters in the range of $\sim$0.8–1.2 mm generated values of $K_{DP}$ that match those observed. They suggested that localized regions of $K_{DP}$ within a range near 0.1–0.2°C km$^{-1}$ in winter storms can be used for identification of regions with active dendritic growth.

Bechini et al. (2011) investigated more than one year of X- and C-band data from stratiform precipitation events in Italy and found enhanced $K_{DP}$ aloft to be very common and independent of the melting-layer height. Their measurements showed proportionally larger values of $K_{DP}$ at the shorter wavelengths, in agreement with scattering calculations. The $K_{DP}$ maximum was consistently located at a temperature level near $\sim$15°C. In agreement with previous studies, they concluded that the enhanced $K_{DP}$ values aloft are most likely produced by platelike crystals.

Williams et al. (2011) collected C-band polarimetric radar data during three winter seasons (2009–11) in Indiana. A total of five winter storms, as well as one summer tropical storm (Hurricane Irene as it made its first landfall), were analyzed. The focus was on $Z_H$ and $Z_{DR}$ measurements. Three winter storms produced enhanced $Z_{DR}$ (observed as layers) from 1 to 3 dB and $Z_H$ from 10 to 30 dB, characterized by dendrites growing in water-saturated conditions and stronger updrafts. The other three storms produced enhanced $Z_{DR}$ (observed as isolated patches and enhancements along the edges of the echoes) from 4 to 8 dB and $Z_H$ from $\sim$10 to 10 dBZ and were characterized by plates growing in ice-supersaturated conditions and weaker updrafts. The authors emphasized the distinction between these two categories and suggested similar analysis could help to detect icing conditions that are hazardous to aviation interests.

Most of these studies are purely observational, only offering hypotheses about the microphysical origins of the observed signature. Although KR11 provide some model calculations, their model only assumes depositional growth and thus is limited in scope. Moreover, their calculations focus mainly on $K_{DP}$ and not on specifically reproducing the observed $Z_{DR}$ and $\rho_{hv}$ profiles. In this study, we aim to build on the study of KR11 by using a more sophisticated microphysical model in an attempt to reproduce the observed signatures in all polarimetric radar variables and to determine the role of different microphysical processes in producing the signature.

3. Case overview

a. Synoptic overview

The main synoptic features of interest are shown in Fig. 1, along with a regional radar mosaic. An upper-level trough, with an intense jet stream (>62 m s$^{-1}$) crossing over Oklahoma, provided favorable dynamical conditions for convective-type mixed winter precipitation. A cold front moved across Oklahoma from the northeast the previous day, putting in place a shallow but stout cold layer near the surface. Through the morning hours on 27 January 2009, ahead of the positively tilted trough, gradually increasing isotropic ascent combined with weak instability aloft was supporting an increase of convectively enhanced winter precipitation rates across much of Oklahoma. During the late afternoon, northerly surface winds behind the cold front continued to advect a subfreezing, low-level air mass over eastern Oklahoma. The strong temperature inversion along with subfreezing temperatures in the lowest portion of the troposphere (below 1 km; see the sounding in Fig. 2) caused the formation of ice pellets and freezing rain in some areas. Relative humidity with respect to water ranged from 80% (at $\sim$5 km) to 100% (at $\sim$3 km), indicating that the atmosphere was supersaturated with respect to ice throughout most of the observed cloud. Also, there was a layer of very strong wind shear below 4 km AGL (the wind speed changed by 31 m s$^{-1}$ in the layer from the surface to 4 km AGL).

During this event, up to 7.6 cm of ice pellets fell in central Oklahoma and nearly 5.1 cm of ice accumulation were reported on power lines in east-central Oklahoma.
These accumulations resulted in more than 50,000 customers losing electrical power in Oklahoma from downed power lines.

b. Observed radar data

Processing of the polarimetric moments usually employs zero-lag estimators of radar variables. In regions of low signal-to-noise ratio, which can be common in winter precipitation, the estimates of $Z_{DR}$ and $\rho_{hv}$ can be biased by noise, obfuscating interpretation of the observations. To avoid these errors, the one-lag estimators of $Z_{DR}$ and $\rho_{hv}$, which are not biased by noise, were used instead of conventional ones (Melnikov and Zrnić 2006). Cloud data were collected at elevation angles up to 60°.
To improve resolution and the number of measurements in the vertical direction, elevation increments of 0.25° were used instead of 1°.

Data were collected with the S-band (11-cm wavelength) polarimetric WSR-88D in Norman, Oklahoma (KOUN). The intrinsic beamwidth of KOUN is about 0.9°. Fields of $Z_H$ and $Z_{DR}$ from the 6.2°-elevation plan position indicator (PPI) scans on 27 January 2009 are shown in Fig. 3. Pockets of enhanced $Z_{DR}$ are evident at each time at a range of about 40 km, initially northwest of the radar and appearing southeast of the radar later, demonstrating the persistence of this feature. This evidence is not to be confused with the melting-layer enhancement of $Z_H$ and $Z_{DR}$, which is located within 20-km range of the radar. RHI s of $Z_H$, $Z_{DR}$, $\rho_v$, and $K_{DP}$ obtained at 2317 UTC (azimuth 181°) are displayed in Fig. 4. Values of $Z_H$ of ~40 dBZ at a height of approximately 1.5 km AGL (herein all heights are AGL) indicate the melting layer “bright band.” Within the melting layer, $Z_{DR}$ is between 1.5 and 2 dB and $\rho_v$ decreases to 0.95. The focus of this study, however, is on the signatures observed at heights of approximately 4.5 and 5 km that are described in the previous section. The $Z_{DR}$ maximum above the melting layer occurs in the temperature range from $-10^\circ$ to $-15^\circ$C, appearing as “pockets” of values as high as 2.5 dB at nearly 5 km, which is coincident with decreased $\rho_v$ to about 0.95. These observations indicate the presence of anisotropic particles such as dendrites or plates. Because this event was convectively enhanced, observed pockets of enhanced $Z_{DR}$ indicate regions of embedded convection. The observed signature is a consequence of different conditions existing within the embedded convection, as compared with the rest of the cloud where the signature is absent. The lack of in situ observations and volumetric radar data leaves the three-dimensional nature and evolution of these regions uncertain, however.

For a quantitative analysis of the observed polarimetric variables, vertical profiles through these pockets are constructed at various ranges from the radar. Profiles are made at 27, 45, and 52 km from the radar (Fig. 4, right panels). These correspond to single range-gate values; no range averaging is performed. In each profile, $Z_H$ and $Z_V$ generally increase toward the melting layer, from near 0 dBZ at cloud top to about 30 dBZ just above the melting layer. The profiles of $Z_{DR}$ start near 0.5 dB at cloud top, increasing abruptly to values as high as 2.5 dB (Fig. 4b) at a height of 4.7 km. The $Z_{DR}$ enhancements...
FIG. 3. Fields of $Z_H$ and $Z_{DR}$ from the 6.2°-elevation PPI on 27 Jan 2009 at four different times as labeled.
encompass a 2-km-thick layer in the range from \(-6^\circ\) to
\(-18^\circ\); \(Z_{\text{DR}}\) then decreases toward the melting layer.
Minimum values just above the melting layer are be-
tween 0.3 and 0.7 dB. Each profile exhibits a \(\rho_{hv}\) mini-
mum coincident with the \(Z_{\text{DR}}\) maximum, with minimum
\(\rho_{hv}\) values of about 0.95. Vertical profiles of \(K_{\text{DP}}\) are
not extracted because the signals are noisy, but a relative
maximum (up to 0.4° km\(^{-1}\)) is evident in the RHI at
ranges of 30–50 km at a height of about 4 km, or about
\(-10^\circ\). These observations are consistent with those
of KR11, although they focused mainly on the \(K_{\text{DP}}\)
enhancement. The depicted polarimetric signature is
not exclusive for winter storms. The pockets of enhanced
\(Z_{\text{DR}}\) coincident with reduced \(\rho_{hv}\) can be observed in
summer thunderstorms, and even in tropical cyclones
(e.g., Williams et al. 2011). The focus of this study is on
winter storms, however, in which the signature is more
common.

4. Model description

To quantitatively explain and interpret the observed
signatures, we develop a microphysical and electro-
magnetic scattering model, which is described below.
a. Microphysical component

A one-dimensional, two-moment, bulk microphysical scheme is developed to explain the observed signatures. There are five ice classes that are categorized by habit: dendritic crystals (herein called dendrites), platelike crystals (herein called plates), needles, near-spherical ice particles, and snow aggregates. Dendrites, plates, near-spherical ice, and needles are initiated according to temperature (Fig. 5) by following the method of Meyers et al. (1992), whereas snow aggregates are formed by self-collection and interaction between other ice classes. Crystal habit depends on temperature as described in Magono and Lee (1966) and Bailey and Hallett (2009). The model assumes an inverse exponential distribution for each of the ice classes, the evolution of which is governed by prognostic equations for mass mixing ratio and total number concentration. For each ice category, we calculate the diagnostic equations for terminal velocity, particle density, and thickness (or vertical dimension of a particle). Mass \( m_x \) (kg), density \( \rho_x \) (kg m\(^{-3}\)), terminal velocity \( v_x \) (m s\(^{-1}\)), and thickness \( H_x \) (m) are calculated using the following power-law relationships (Matrosov et al. 1996; Pruppacher and Klett 1997; Straka 2009):

\[
\begin{align*}
m_x &= aD_{nx}^b, & v_x &= cD_{nx}^d, & \rho_x &= eD_{nx}^f, & H_x &= gD_{nx}^h, \\
\end{align*}
\]

(1)

where \( D_{nx} \) represents the horizontal length of a crystal in meters. The values of the parameters \( a–h \) are given in Table 2. The density of snow aggregates ranges from 0.08 down to 0.02 g cm\(^{-3}\). The range of densities of each pristine ice crystal is shown in Fig. 5.

All equations are integrated using the finite-difference method on a staggered grid. For all spatial derivatives we have used second-order centered differences, and a leapfrog scheme was used for time derivatives. The model time step is 0.5 s, the spatial resolution is 25 m, and the domain height is 10 km. The model was initiated with temperature, water vapor mixing ratio, and pressure from the 0000 UTC 28 January 2009 sounding from Norman (see Fig. 2). For simplicity, saturation with respect to water \( S_w \) is set to a constant value of 1.0 and saturation with respect to ice \( S_i \) is calculated as a function of ambient temperature from the sounding. The microphysical scheme includes the following processes: nucleation of ice crystals, depositional growth, and aggregation. Each of these processes is described below.

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**Table 2. Values of parameters for power-law relationships.** See Eq. (1) in the text. Units of \( a, c, e, \) and \( g \) are arbitrary. Parameters \( b, d, f, \) and \( h \) are dimensionless. Relations produce units of kilograms, meters per second, kilograms per meter cubed, and meters for mass, terminal velocity, density, and thickness, respectively. Values come from Pruppacher and Klett (1997), Straka (2009), and Matrosov et al. (1996), although units have been converted so that the results are in standard mks units.

<table>
<thead>
<tr>
<th></th>
<th>Mass</th>
<th>Terminal velocity</th>
<th>Density</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( a )</td>
<td>( b )</td>
<td>( c )</td>
<td>( d )</td>
</tr>
<tr>
<td>Dendritic crystals</td>
<td>2.989</td>
<td>2.83</td>
<td>17.899</td>
<td>0.62</td>
</tr>
<tr>
<td>Needles</td>
<td>4.038</td>
<td>2.6</td>
<td>73.53</td>
<td>0.65</td>
</tr>
<tr>
<td>Plates</td>
<td>156.74</td>
<td>3.31</td>
<td>5.016</td>
<td>0.48</td>
</tr>
<tr>
<td>Near-spherical ice</td>
<td>156.74</td>
<td>3.31</td>
<td>5.016</td>
<td>0.48</td>
</tr>
<tr>
<td>Snow</td>
<td>0.4555</td>
<td>2.4</td>
<td>4.8367</td>
<td>0.25</td>
</tr>
</tbody>
</table>
Nucleation of ice particles includes depositional and contact nucleation. The number of ice nuclei initiated by deposition and by contact is a function of temperature and supersaturation and is determined using a parameterization described by Meyers et al. (1992) as

\[ N_{id} = 1000 \exp[12.96(S_i^5 - 1) - 0.639], \]  

(2)

where \( N_{id} \) is the number of nucleated crystals (m\(^{-3}\)). Potential contact-freezing concentrations (m\(^{-3}\)) were parameterized according to Meyers et al. (1992) as

\[ N_{ic} = 1000 \exp[-2.8 + 0.262(T_0 - T)], \]  

(3)

where \( T \) is the cloud droplet temperature and \( T_0 = 273.15^\circ\text{C} \). According to this mode of nucleation, ice cannot be formed at temperatures warmer than \(-5^\circ\text{C}\). It is assumed that contact-freezing nuclei have a size of 0.1 \( \mu \text{m} \). Crystal habit is determined by the temperature, as in Magono and Lee (1966) and Bailey and Hallett (2009) (see Fig. 5).

Ice crystals can grow by diffusion of water vapor onto the particle, increasing ice mass directly through deposition. This process occurs when the environment is supersaturated with respect to ice. Particles that grow by deposition are dendrites, plates, needles, near-spherical ice particles, and snow aggregates. The depositional growth equation assumes an inverse exponential particle size distribution following that of Pruppacher and Klett (1997). Ventilation factors for particles with diameters greater than 120 \( \mu \text{m} \) are included in the growth equation.

Aggregation contains two processes: 1) self-collection of dendrites, plates, needles, and snow aggregates and 2) collection of dendrites, plates, and needles by snow aggregates and collection of plates and needles by dendrites. The growth equation for self-collection is given according to Passarelli and Srivastava (1979). The continuous growth equation for collection of crystals of different habits is from Gilmore et al. (2004). Collection efficiencies for each ice class are as given by those papers, and the collision kernel includes the velocity correction by Murakami (1990).

b. Scattering component

The polarimetric radar variables depend on the size, shape, and orientation of hydrometeors within the sampling volume, as well as on the dielectric constant, which is a function of hydrometeor density, water content, temperature, and the wavelength of the incident radiation. Thus, output of the microphysical model is used to compute the polarimetric radar variables for each ice class, as well as the “bulk” variables (summed contributions from each individual ice class). The prognostic moments (mass mixing ratio and total number concentration) are used to determine the particle size distribution (PSD) of each ice hydrometeor species. These PSDs are then divided into 80 particle size “bins.” The width of the bins (as well as the minimum and maximum particle sizes) for each ice class is shown in Table 3. The axis ratios of the particles are computed from the power-law relations given at the beginning of section 4.

The Maxwell Garnett (1904) mixing formula is used for calculating the dielectric constant. The dielectric constant of dry snow \( \varepsilon_i \) is determined by the volume fraction of ice \( f_{vi} \) \[ f_{vi} \approx \rho_i/\rho_s, \] where \( \rho_i \) is the particle density and \( \rho_s (=917 \text{ kg m}^{-3}) \) is the density of solid ice in the mixture with air and dielectric constants of ice \( \varepsilon_i \) and air \( \varepsilon_a \). Assuming that \( \varepsilon_a \approx 1 \), we obtain

\[ \varepsilon_j = \frac{1 + 2f_{vi}\varepsilon_i - 1}{1 - 2f_{vi}\varepsilon_i + 2}. \]  

(4)

It is assumed that the particles are oriented horizontally but that they experience fluctuations in their orientations. A two-dimensional axisymmetric Gaussian distribution of canting angles is used for dendrites, plates, and snow aggregates. Angular moments for the distribution of orientation angles are as given by Ryzhkov (2001) and Ryzhkov et al. (2011). In this study, the mean orientation angle is 0° with respect to the vertical axis, with a distribution width of \( \sigma = 12^\circ \) for dendrites and plates (Matrosov et al. 2004). For snow aggregates, \( \sigma = 40^\circ \) and no canting angle fluctuations are used for near-spherical particles whereas needles are characterized by random fluctuations in the horizontal plane.

The Rayleigh approximation is used to compute the complex scattering amplitudes for each particle. This approximation is valid because the model considers ice particles that are all much smaller than the radar
wavelength. The scattering amplitudes are converted into the S-band (11-cm wavelength) polarimetric radar variables by following the method of Ryzhkov et al. (2011).

5. Results and discussion

The default model output is herein referred to as the base run, which will be used in comparisons with sensitivity experiments. The modeled vertical profiles of the bulk polarimetric radar variables for the base-state model run are presented in Fig. 6. Because the focus of this study is on the polarimetric signatures above the melting layer, the profiles are only calculated above the $0^\circ$C level (2 km).

The $Z_H$ and $Z_V$ profiles (Fig. 6) increase gradually from 0 dBZ at about 6.6 km to a maximum of 30.3 dBZ at 3.2 km. Thereafter, they remain approximately constant toward the melting layer. Near the top of the profile (above 6 km), the very low (<10 dBZ) $Z_H$ values are produced by near-spherical ice particles (Fig. 7). Starting just below 6 km, the contribution from plates dominates the overall $Z_H$, until their $Z_H$ begins decreasing as the plates aggregate. Aggregation of plates
transfers mass to the snow-aggregates species, increasing the $Z_H$ contribution from snow aggregates starting at 5.4 km. Dendrites appear at 5 km, with their $Z_H$ reaching a maximum at 4.5 km, although the overall signal is dominated by contributions from snow aggregates. Needles appear at about 4.3 km, although their overall $Z_H$ is negligibly small ($<0 \text{ dB}$) and does not affect the overall bulk $Z_H$. The $Z_H$ contribution from dendrites (plates) becomes insignificant ($<0 \text{ dBZ}$) at about 3.5 (4.4) km as the mass from these categories has been entirely transferred into snow aggregates. The bulk $Z_H$ decreases below 3 km as self-collection of snow aggregates decreases their total number concentration (while mass remains constant). Because the same partitioning of the PSDs is used at all levels to calculate the polarimetric variables, a negative bias is introduced in the computed $Z_H$ because the maximum particle size is fixed (cf. Table 3).

The bulk $Z_{DR}$ profile remains low ($<0.5 \text{ dB}$) at cloud top before increasing dramatically to a maximum of nearly 6 dB at 5.4 km (Fig. 6). The maximum is produced by the high-density, anisotropic plates (not shown). The $Z_{DR}$ then decreases as the plates begin to aggregate and the $Z_H$ from snow aggregates begins to dominate the $Z_H$ of plates. There is a secondary maximum in $Z_{DR}$ at about 4.6 km produced by dendrites. The intrinsic $Z_{DR}$ of the dendrites at this level is about 3.4 dB; the maximum in the bulk profile is much smaller (1.1 dB), however, owing to the larger $Z_H$ of snow aggregates. Below 4 km, the $Z_{DR}$ from snow aggregates is $<0.1 \text{ dB}$ owing to their very low density (0.02–0.2 g cm$^{-3}$) and increased wobbling ($\sigma = 40^\circ$). Needles do not affect the bulk $Z_{DR}$ because their contribution to $Z_H$ is negligibly small.

At the top of the cloud, the bulk $\rho_{hv}$ profile (Fig. 6) is nearly 1.0 owing to the presence of the near-spherical ice particles. Below 6 km, $\rho_{hv}$ begins to decrease, reaching its first minimum of 0.935 at 5.6 km before increasing to a relative maximum of 0.965 at 5.4 km, followed by a second minimum (0.927) at 5.2 km. This peculiar behavior in $\rho_{hv}$ is elucidated by considering the $Z_H$ profiles (Fig. 7). The first minimum in $\rho_{hv}$ is caused by a mixture of near-spherical ice particles and plates, which have comparable contributions to $Z_H$ at that level. As the contribution to $Z_H$ of near-spherical ice decreases and the $Z_H$ of plates increases, the bulk signal becomes dominated by plates, leading to an increase in $\rho_{hv}$. The $\rho_{hv}$ then decreases again owing to a mixture of ice crystal habits as the $Z_H$ of snow aggregates increases and becomes comparable to that of plates. As snow aggregates begin to dominate the $Z_H$, the $\rho_{hv}$ increases, eventually reaching to near 1.0 below 4 km.

Specific differential phase shift $K_{DP}$ is low throughout the domain but features two localized maxima located at 5.2 and 4.5 km (Fig. 6). The maximum aloft (0.0032° km$^{-1}$) is produced by plates, whereas the maximum below (0.0025° km$^{-1}$) is produced by dendrites. These simulated $K_{DP}$ maxima are two orders of magnitude lower than what is observed in our case, as well as those of KR11. Note that the $K_{DP}$ maxima are located 0.2 and 0.9 km below the $Z_{DR}$ maxima produced by each species, however, as has been observed in past studies (e.g., Ryzhkov and Zrnić 1998; KR11). The difference in altitude of the signatures can be attributed to the fact that $K_{DP}$ is dependent on concentration whereas $Z_{DR}$ is not. The $Z_{DR}$ maximum appears above the enhancement of
$K_{DP}$ because plates are present, but in low enough concentration so as not to produce any enhancement of $K_{DP}$; rather, $K_{DP}$ is enhanced as the concentration of plates becomes sufficiently large. Differential reflectivity $Z_{DR}$ tends to be decreased at this level because of the production of snow aggregates.

The base model run reproduces the general profile and magnitude of the observed $Z_H$ and $\rho_v$, and the correct shape (but not magnitude) of $Z_{DR}$ and $K_{DP}$ relative to the radar observations. Also, in our case, plates produce the dominant $Z_{DR}$ and $K_{DP}$ enhancements, in contrast to KR11’s hypothesis that dendrites produce the $K_{DP}$ enhancement. Because of the discrepancies between our model results and KR11’s results and with our observations, we have conducted a series of sensitivity experiments that address these differences. Additional sensitivity experiments are designed because the magnitudes of the simulated $Z_{DR}$ and $K_{DP}$ enhancements do not agree with the observations.

KR11 were able to match their observed $K_{DP}$ values (but not $Z_{DR}$) with simple scattering calculations using assumed PSDs. Comparison of their PSD parameter space and our simulated PSDs (Fig. 8) reveals a large discrepancy. Because $K_{DP}$ depends on concentration, we have conducted a series of sensitivity experiments that increase the concentration of dendrites.\(^1\)

The discrepancy between the results of KR11 and ours can be explained upon comparison of the PSDs used in each study (Fig. 8). It is clear that the model-simulated PSDs have much shallower slopes than those used in KR11. Although observations of snow size spectra aloft are rare, note that both sets of PSDs are within the range of the aircraft observations presented in Lo and Passarelli (1982). In addition, KR11 partition a single PSD, with sizes of less than 3.0 mm treated as dendrites and larger particles treated as snow aggregates. The microphysical model used here assigns each ice class its own PSD. This leads to several important differences:

1) The concentration of dendrites that are less than 1 mm in size is 200 times as large in KR11 as that predicted by our model, whereas their largest dendrites are nearly two orders of magnitude smaller in concentration.

2) The snow aggregate PSD in KR11 shown here has no particles with concentration in excess of 1 $m^{-3} \text{ mm}^{-1}$, whereas all snow aggregates smaller than 4 mm in our model have concentrations larger than 1 $m^{-3} \text{ mm}^{-1}$.

3) The largest snow aggregates in our model have concentrations that are several orders of magnitude larger than the largest particles in the calculations of KR11.

For difference 1, KR11 also show (their Fig. 18) that the maximal contribution to $K_{DP}$ comes from the smaller (<1–2 mm) dendrites; thus, it is expected on the basis of the difference in PSDs that their calculations would result in much larger $K_{DP}$ values than those predicted in our model. In addition, the computed $Z_{DR}$ in KR11 is much larger than their observations. This may be because of differences 2 and 3 above, wherein the concentration of snow aggregates (and especially the larger aggregates) is too low to produce enough $Z_H$ to offset the intrinsic high $Z_{DR}$ of dendrites. As shown above, the simulated bulk $Z_{DR}$ in dendrites in this study is lower, owing to the higher concentration of snow aggregates. These important differences will guide our choices in the sensitivity experiments.

The sensitivity experiments are summarized in Table 4. Each experiment makes incremental changes to the base-state simulation. In Exp1, the base state is reproduced, but plates are excluded from the microphysics. In Exp2, the dendrite concentration is increased by 100, 150, and 200 times the base-state dendrite concentration (Exp2a, Exp2b, and Exp2c, respectively). Exp3 excludes plates and increases dendrite concentration by 70, 100, and 200 times the base-state concentrations (Exp3a, Exp3b, and Exp3c, respectively). In Exp4, the base state

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\(^1\) Note that the slope parameter of the PSD is constrained by the model microphysics, and thus it cannot be altered.
is reproduced but the \( \sigma \) of dendrites and plates is increased from 12° to 20°, 30°, and 35° (Exp4a, Exp4b, and Exp4c, respectively).

In general, it is clear from Table 4 that none of the experiments was able to reproduce all extrema in the polarimetric variables. Selected experiments are plotted in Figs. 9 and 10 along with the base state for closer analysis. The configuration for Exp1 (Fig. 9, top panels) excludes plates from the microphysics scheme but is otherwise identical to the base run. The resulting \( Z_H \) profile changes shape, abruptly increasing from \( \approx 5 \) dBZ at 5.6 km to 30 dBZ at 4.7 km. Without plates, dendrites are no longer competing for vapor, which increases their concentration and depositional growth and consequently their \( Z_H \). The \( Z_{DR} \) profile is in closer agreement with the observations (maximum 3.4 dB) than is the base state (maximum 5.9 dB). This is because dendrites have lower intrinsic \( Z_{DR} \) than plates owing to their lower density. The \( \rho_H \) profile again displays two minima, for the same reasons as the base state (but with dendrites instead of plates). The \( K_{DP} \) maximum is correctly produced just below the \( Z_{DR} \) maximum; the maximum value of \( K_{DP} \) (0.006° km\(^{-1}\)) is still far too low, however.

Exp2c is plotted in the bottom panels of Fig. 9. Plates are included in the microphysics scheme, but this time the dendrite concentration is increased by a factor of 200 (approximately what is necessary to match the PSD intercept parameter of KR11). The \( Z_H \) profile is significantly altered, revealing a midlevel maximum in \( Z_H \) at 4.5 km, with maximum values reaching 46.9 dBZ. In addition, the bulk \( Z_{DR} \) has a secondary maximum (3.3 dB) beneath the maximum produced by plates. Correlation coefficient \( \rho_H \) increases to 0.99 in the region of dendrites, whereas \( K_{DP} \) now shows a large maximum (0.43° km\(^{-1}\)) at 4.5 km. Although the \( K_{DP} \) profile is consistent with the observations, the resulting \( Z_H \) and \( Z_{DR} \) profiles are inconsistent in magnitude and shape.

The top panels in Fig. 10 show the results of Exp3a, which excludes plates from the microphysics scheme and increases the dendrite concentration to 70 times that of the base-state run. Recall from Exp1 that excluding plates increases the concentration of dendrites (through lack of competition). Thus, the dendrite concentration does not have to be increased as dramatically to reproduce the observed \( K_{DP} \) maximum (about 0.4° km\(^{-1}\)). Otherwise, the simulated profiles are similar to those of Exp1 and Exp2c.

Exp4c (bottom panels of Fig. 10) is identical to the base state except that \( \sigma \) for dendrites and plates is increased, allowing for more wobbling. As expected, \( Z_H \) does not change much from the base state, as the increase in \( \sigma \) mainly affects \( Z_{DR} \), \( \rho_H \), and \( K_{DP} \). The resulting \( Z_{DR} \) and \( \rho_H \) profiles are the closest to the observed profiles of all the experiments. Although the \( K_{DP} \) profile has a maximum beneath the \( Z_{DR} \) maximum, its value is again far too low. Thus, this experiment matches three of the four variables to the observations.

The base-state simulations assume \( \sigma = 12^\circ \) for dendrites and plates, based on Matrosov et al. (2004). The value chosen in Exp4c (35°) is larger than is seen in the very few observations available and thus may not be physical. Future observational studies may investigate the range of values found in nature for \( \sigma \).

To summarize the sensitivity experiments, excluding the plates (Exp1) produces a \( Z_{DR} \) profile that is consistent with the observations, whereas \( Z_H \), \( \rho_H \), and \( K_{DP} \) are all inconsistent. The \( K_{DP} \) profile matches the observations if the concentration of dendrites is increased (Exp2), but the rest of the profiles do not agree with the observations. The results of Exp3 are similar to those of Exp2 (i.e., increased dendrite concentration with plates removed produces similar results to the ones obtained by increasing dendrite concentration with plates included). Last, the profiles of \( Z_H \), \( Z_{DR} \), and \( \rho_H \) with increased \( \sigma \) (Exp4) are consistent with the observations, but there is no \( K_{DP} \) maximum produced. Thus, the model is incapable of matching both the observed magnitude and the shape of all polarimetric variables. A full explanation of the
Fig. 9. Vertical profiles of the bulk $Z_{H}$, $Z_{DR}$, $\rho_{hv}$, and $K_{DP}$ for the various sensitivity experiments (in each panel, the base state is indicated by the black solid line): (top) Exp1 (dotted line), which is identical to the base state except that plates are excluded, and (bottom) Exp2c (dashed lines), which is identical to the base state but the dendrite concentration is enhanced by 200 times. See Table 4 and the text for details.
FIG. 10. As in Fig. 9, but for (top) Exp3a (gray dashed line), which excludes plates and enhances the dendrite concentration by 70 times, and (bottom) Exp4c (gray dashed lines), which is identical to the base state except that particles have an increased distribution width of canting angles.
signature requires that the profiles of all polarimetric variables (magnitude and shape) are reproduced as observed. Although KR11 and our model can reproduce some of the observations, neither can fully explain all observed signatures. KR11 assume PSDs that are consistent with limited observational studies, whereas our model simulates PSDs (based on accepted parameterizations of ice nucleation, vapor deposition, and aggregation) that are also found to be consistent with the limited observations. Therefore, a more complete explanation may require inclusion of additional processes into the microphysical model.

The sensitivity experiments demonstrate that increasing the concentration of dendrites can reproduce the $K_{DP}$ signature but causes $Z_H$ to grow excessively large. This is because the simulated PSD slopes are shallow, and therefore increasing the concentration of the larger dendrites causes $Z_H$ to grow too high. Instead, steeper PSDs (such as those used in KR11) can produce the $K_{DP}$ and $Z_H$. KR11 have PSDs that produce $Z_{DR}$ that is too high, however. This is because their assumption about partitioning the PSDs causes very low concentrations of aggregates. The aggregates serve to bring down the intrinsically high $Z_{DR}$ of the pristine crystals, but they must have sufficient $Z_H$ to do so. This is achieved with a physically consistent model that accounts for the aggregation process. Thus, the recipe for reproducing all signatures may be a PSD of anisotropic pristine crystals with steeper slope (but larger intercept parameter), as well as a sufficiently large concentration of aggregates. In physical terms, this means a much larger concentration (at least two orders of magnitude more; see Table 4) of the smaller pristine crystals is required. The Hallett–Mossop (1974) ice multiplication (H-M) mechanism is a possible candidate for a process that can substantially increase the concentration of very small, pristine crystals without increasing the concentration of larger pristine ice. The addition of these newly generated tiny crystals would not substantially affect $Z_H$ (or $Z_{DR}$ if aggregates are present in sufficiently large concentrations) but would increase $K_{DP}$. The H-M mechanism requires special temperature conditions ($-3^\circ C > T > -8^\circ C$) in which riming occurs (liquid droplets of $\approx 25 \mu m$ must be present). Rimming requires updrafts, which can produce water-saturated conditions that promote rapid depositional growth of ice crystals. Note that Hogan et al. (2002) also proposed the H-M mechanism as an explanation for enhanced $Z_{DR}$ found above the melting layer in stratiform clouds, on the basis of combined polarimetric radar and aircraft observations. The enhancements of $Z_{DR}$ and $K_{DP}$ in the case presented here occur at higher altitudes (colder temperatures), outside the range of conditions required for the H-M mechanism, however.

In this study, the modeled ice crystals are initiated following the well-known Meyers et al. (1992) parameterization, which determines ice crystal number concentration using only the environmental temperature and supersaturation with respect to ice. Recent observations (Westbrook and Illingworth 2011) indicate that initiation of ice crystals via the liquid phase (i.e., in the presence of supercooled liquid droplets) is extremely important, however, especially in clouds within the temperature range of this case. Such initiation is not accounted for in our model but may represent an additional source of ice production, which would affect the resulting PSDs by increasing the concentration of smaller (<1-mm equivalent diameter) pristine crystals. Thus, we speculate that such secondary ice initiation may be the most likely candidate in our case and in similar cases in which the $Z_{DR}$ and $K_{DP}$ enhancements are located outside the range from $-3^\circ$C to $-8^\circ$C. Such processes should be included in future studies, because a more realistic representation of all relevant microphysics may improve explanations of the signature.

6. Conclusions

Dual-polarization radar observations above the melting layer in winter storms reveal a layer or pockets of enhanced $Z_{DR}$ and $K_{DP}$ and reduced $\rho_{hv}$ (e.g., Bader et al. 1987; Ryzhkov et al. 1998; Wolde and Vali 2001; Hogan et al. 2002; Bechini et al. 2011; KR11). We present similar observations from 27 January 2009, in which the $Z_{DR}$ maximum and $\rho_{hv}$ minimum are located between approximately $-10^\circ$ and $-15^\circ$C and the $K_{DP}$ maximum is located at a slightly lower height. A two-moment bulk microphysical model is coupled with electromagnetic scattering calculations to interpret and explain the signature. This model includes only ice initiation, vapor deposition, and aggregation. The model reproduces several of the observed features, including the shape of the $Z_H$, $Z_{DR}$, $K_{DP}$, and $\rho_{hv}$ profiles; there are some discrepancies, however: the magnitudes of the $Z_{DR}$ and $K_{DP}$ extrema are not accurately reproduced. Sensitivity calculations demonstrated that the model is able to reproduce any one of the observed profiles but not all four polarimetric variables simultaneously, implying that some processes may have been neglected.

A schematic illustrating vertical profiles of the polarimetric radar variables above the melting layer and our proposed explanation is presented in Fig. 11. At cloud top, located nearly 5 km above the melting level, small, quasi-spherical ice crystals are initiated. These crystals produce very low $Z_H$, $Z_{DR}$, and $K_{DP}$ and high $\rho_{hv}$. These crystals and subsequently initiated ones at lower altitudes grow by vapor deposition to high-density, platelike
hhabits, producing a rapid increase in $Z_{DR}$ and decrease in $\rho_{HV}$ between 2 and 3 km above the melting level. The maximum in $Z_{DR}$ arises because of the high particle density and very anisotropic shape, while the diversity of particle shapes and orientations reduces $\rho_{HV}$. The $Z_{DR}$ maximum is lower than the intrinsic $Z_{DR}$ of the pristine crystals because of the presence of aggregates. There are no local maxima in $ZH$ and $K_{DP}$ at this altitude. As the pristine crystals begin to aggregate, $Z_{DR}$ decreases and $ZH$ increases because the particles become larger but less dense and more spherical. This also increases $\rho_{HV}$. Centered just 2 km above the melting level (but below the $Z_{DR}$ maxima), a $K_{DP}$ maximum appears. Note that the $K_{DP}$ maximum is located in the region of decreasing $Z_{DR}$. We speculate that some sort of secondary ice production [e.g., ice nucleation via the liquid phase, as in Westbrook and Illingworth (2011)] produces small but very anisotropic crystals (in large concentrations) with preferential horizontal orientation. Though not contributing much backscattered power relative to the larger snow aggregates, they produce an observable increase in the forward-propagation differential phase. Future studies employing more sophisticated microphysics (including riming and secondary ice production) should be made to determine which processes can explain all of the observed profiles of the polarimetric variables.

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REFERENCES


