The Anatomy and Physics of Z\textsubscript{DR} Columns: Investigating a Polarimetric Radar Signature with a Spectral Bin Microphysical Model

MATTHEW R. KUMJIAN\textsuperscript{*}
Advanced Study Program, National Center for Atmospheric Research, Boulder, Colorado

ALEXANDER P. KHAIN, NIR BENMOSHE, AND EYAL ILOTOVIZ
Hebrew University of Jerusalem, Jerusalem, Israel

ALEXANDER V. RYZHKOV
Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma, Norman, Oklahoma

VAUGHAN T. J. PHILLIPS
Department of Physical Geography and Ecosystem Science, Lund University, Lund, Sweden

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ABSTRACT

Polarimetric radar observations of deep convective storms frequently reveal columnar enhancements of differential reflectivity $Z_{\text{DR}}$. Such “$Z_{\text{DR}}$ columns” can extend upward more than 3 km above the environmental 0°C level, indicative of supercooled liquid drops being lofted by the updraft. Previous observational and modeling studies of $Z_{\text{DR}}$ columns are reviewed. To address remaining questions, the Hebrew University Cloud Model, an advanced spectral bin microphysical model, is coupled with a polarimetric radar operator to simulate the formation and life cycle of $Z_{\text{DR}}$ columns in a deep convective continental storm. In doing so, the mechanisms by which $Z_{\text{DR}}$ columns are produced are clarified, including the formation of large raindrops in the updraft by recirculation of smaller raindrops formed aloft back into the updraft at low levels. The internal hydrometeor structure of $Z_{\text{DR}}$ columns is quantified, revealing the transition from supercooled liquid drops to freezing drops to hail with height in the $Z_{\text{DR}}$ column. The life cycle of $Z_{\text{DR}}$ columns from early formation, through growth to maturity, to demise is described, showing how hail falling out through the weakening or ascending updraft bubble dominates the reflectivity factor $Z_{\text{H}}$, causing the death of the $Z_{\text{DR}}$ column and leaving behind its “ghost” of supercooled drops. The height of the $Z_{\text{DR}}$ column is correlated with updraft strength, and the evolution of $Z_{\text{DR}}$ column height is correlated with increases in $Z_{\text{H}}$ and hail mass content at the ground after a lag of 10–15 min.

1. Introduction

For several decades, dual-polarization radar measurements of deep moist convective storms have provided numerous insights into the microphysical structure of such storms. The information is inferred from the polarimetric radar variables, which are related to the size, shape, composition, and orientation of precipitation particles in storms. The polarimetric radar variables are reflectivity factor at horizontal polarization $Z_{\text{H}}$, differential reflectivity $Z_{\text{DR}}$, specific differential phase $K_{DP}$, copolar correlation coefficient $\rho_{hh}$, and linear depolarization ratio LDR. One can find more information about these variables and their physical meaning in the textbooks of Doviak and Zrnić (1993) and Bringi and Chandrasekar (2001), as well as in numerous review papers in the scientific literature (e.g., Herzegh and Jameson 1992; Hubbert et al. 1998; Zrnić and Ryzhkov...
One of the most notable polarimetric radar signatures in convective storms is the so-called $Z_{DR}$ column. A $Z_{DR}$ column can be defined as a narrow (generally a few kilometers wide) vertical extension of positive $Z_{DR}$ values above the environmental 0°C level associated with the updrafts in deep moist convective storms. If the storm’s updraft is strong enough to produce a weak echo region (WER), the $Z_{DR}$ column is often found within or on the periphery of the WER. In extreme cases, the $Z_{DR}$ column may extend as much as 3.0 km or more above the environmental 0°C level. An example of a $Z_{DR}$ column is shown in Fig. 1. The data were collected with the research Weather Surveillance Radar-1988 Doppler polarimetric (WSR-88DP) type of radar in Norman, Oklahoma (KOUN), and show a genuine range–height indicator (RHI) scan or vertical cross section through a deep convective storm exhibiting an overshooting top. At a range of about 74 km, along the leading edge of the storm, there exists a tall, columnar region of enhanced $Z_{DR}$. The 1-dB $Z_{DR}$ contour extends more than 1.5 km above the environmental 0°C level, which is at ~3.5 km above ground level (AGL) in this case. Near the top of the $Z_{DR}$ column is a small region of negative $Z_{DR}$ (values from ~0.4 to ~0.1 dB). Just uprange of the $Z_{DR}$ column is a $Z_{DR}$ “hole” or notch coincident with large (>60 dBZ) $Z_H$ values, indicating a shaft of larger hailstones. These features are common in deep convective storms.

In Fig. 1, very large $Z_{DR}$ values are found below ~3 km, indicating the presence of large raindrops associated with the storm’s updraft. According to classical theory, observations, and simulations, the first raindrops in continental convective cloud updrafts should form aloft (e.g., Freud and Rosenfeld 2012; Benmoshe et al. 2012; Khain et al. 2013). Because of the large cloud condensation nuclei (CCN) concentrations found in continental environments such as Oklahoma, convective updrafts are characterized by large number concentrations of small drops that by themselves are not conducive to coalescence growth into large drops, particularly at low levels. Thus, the mechanism for the growth of the large raindrops responsible for observed $Z_{DR}$ columns needs to be clarified.

The anatomy and physics of $Z_{DR}$ columns are the subjects of this paper. The purposes of this study are

1) to clarify the mechanism by which $Z_{DR}$ columns are produced,
2) to quantify the internal hydrometeor structure within the updraft and $Z_{DR}$ columns at various heights,
3) to document/describe the life cycle of a $Z_{DR}$ column,
4) to quantify the relation between $Z_{DR}$ column life cycle and other storm attributes (echo top, maximum low-level $Z_H$, updraft intensity, etc.), and
5) to understand how $Z_{DR}$ columns relate to precipitation formation in deep convective clouds.

We tackle these scientific objectives by using a sophisticated spectral bin microphysics model, which is described in section 3. The formation and life cycle of simulated $Z_{DR}$ columns are detailed in section 4. Section 5 presents the anatomy of $Z_{DR}$ columns, including simulated particle distributions of various hydrometeor species at different times during a $Z_{DR}$-column life cycle. Section 6 discusses practical implications of $Z_{DR}$ columns. First,
however, we provide a comprehensive literature review of previous studies of $Z_{\text{DR}}$ columns in section 2.

2. Background

a. Observations of $Z_{\text{DR}}$ columns

Examples of $Z_{\text{DR}}$ columns were first documented in the 1980s. Perhaps the first paper to show (but not discuss) a $Z_{\text{DR}}$ column is Hall et al. (1980). Later, Hall et al. (1984) documented a $Z_{\text{DR}}$ column extending 1.5 km above the 0°C level, suggesting it contained supercooled liquid drops lofted by the updraft. They also noted negative $Z_{\text{DR}}$ values atop the column. Illingworth et al. (1987) were the first to explore $Z_{\text{DR}}$ columns in detail. They considered various types of particles that could possibly cause a $Z_{\text{DR}}$ enhancement above the 0°C level and concluded that $Z_{\text{DR}}$ columns likely comprise sparse concentrations of large (>4 mm) raindrops. They found that $Z_{\text{DR}}$ columns occurred in the developing stages of cumulus convection and extended from the ground upward to temperatures as low as $-10^\circ$C, where some of the lofted drops could serve as efficient hail embryos.

These authors suggested that wet particles within the melting layer were not the source of the particles in the column; rather, the source was condensation and coalescence growth of large raindrops as they descended through the updraft. They also noted that the growth of $Z_{\text{DR}}$ columns above the 0°C level preceded the $Z_{\text{HI}}$ echo-top ascent and suggested that early low-$Z_{\text{HI}}$, high-$Z_{\text{DR}}$ precipitation echoes were likely to intensify. The $Z_{\text{DR}}$ columns in their study were transient features, with lifetimes of less than 10 min.

Caylor and Illingworth (1987) concluded that the only tenable hypothesis for the anomalously large $Z_{\text{DR}}$ values was the presence of large drops (they focused mainly on the lower portions of the $Z_{\text{DR}}$ columns). They suggested that ultragiant nuclei could serve to grow such large drops, and they developed a model to test their suggestion. Their modeled $Z_{\text{DR}}$ values were larger than the observations, although they were not entirely inconsistent. In this case, traditional coalescence growth could not be ruled out. In a follow-up study, Illingworth (1988) also suggested that the large drops may be grown on ultragiant nuclei. In a study of a microburst-producing storm, Tuttle et al. (1989) documented a $Z_{\text{DR}}$ column extending more than 3 km above the 0°C level and noted that the storm’s first echo was below the melting level, suggesting precipitation development was through warm-rain processes (e.g., accretion and coalescence growth). Updraft speeds of 25–30 m s$^{-1}$ were closely associated with the mature $Z_{\text{DR}}$ column. Later, updraft weakening coincided with the column shrinking.

As polarimetric radar observations became increasingly common over the next few years, more $Z_{\text{DR}}$ columns were documented (e.g., Wakimoto and Bringi 1988; Shupyatsky et al. 1990; Balakrishnan and Zrnić 1990; Vivekanandan et al. 1990; Bringi et al. 1991; Meischner et al. 1991; Herzegh and Jameson 1992; Conway and Zrnić 1993; Ryzhkov et al. 1994; Höller et al. 1994; Raghavan and Chandrasekar 1994; Yuter and Houze 1995). The paper by Bringi et al. (1991) paired radar observations with aircraft penetrations in studying the life cycle of ordinary convective storms. The aircraft penetrations revealed very large (up to 7 mm in diameter) drops below the melting level in the high-$Z_{\text{DR}}$ regions, which were coincident with aircraft-detected updraft peaks. During cell-decaying phases, no $Z_{\text{DR}}$ columns were present. Bringi et al. (1991) were also the first to point out the importance of size sorting in $Z_{\text{DR}}$ columns, as large drops grow by collection of smaller cloud droplets as they fall, whereas smaller drops are lofted by the updrafts. In addition, enhanced X-band attenuation was noted atop the $Z_{\text{DR}}$ column.

Dual-Doppler observations of a supercell by Conway and Zrnić (1993) allowed the computation of particle trajectories to explore the $Z_{\text{DR}}$ column origin and hail growth. They found that ice particles from the backscatter anvil were recirculated into the updraft after melting, forming the $Z_{\text{DR}}$ column on the northwest periphery of the main updraft core. Below the melting layer, the $Z_{\text{DR}}$ column consisted of large raindrops, whereas they determined that above the melting layer the $Z_{\text{DR}}$ column comprised a mixture of supercooled drops, water-coated ice particles, “wet oblate structures,” and spherical ice particles. They surmised that these particles would become efficient hail embryos.

Conway and Zrnić (1993) also made a distinction between this mature $Z_{\text{DR}}$ column in a supercell and those in earlier works that were found in developing cumulus clouds. Along with Conway and Zrnić (1993), Shupyatsky et al. (1990) and Ryzhkov et al. (1994) suggested that $Z_{\text{DR}}$ columns could be used in clarifying the regions of hail growth in developing convective storms. Ryzhkov et al. (1994) also emphasized the importance of $Z_{\text{DR}}$ columns in locating the updraft, particularly when only single-Doppler data are available.

Aircraft penetrations supplemented polarimetric radar observations in the studies of Brandes et al. (1995) and Bringi et al. (1996, 1997). Each study observed very large raindrops (some up to 8 mm in diameter) within $Z_{\text{DR}}$ columns, which were found in close vicinity to updrafts. Bringi et al. (1997) found a mixture of liquid and frozen drops along with ice crystals and graupel within the updraft at a temperature level of $-6.5^\circ$C. Those authors also documented the disappearance of the $Z_{\text{DR}}$
column as the updraft bubble ascended, leaving behind a region of predominantly downdrafts.

Reductions in $\rho_{ho}$ and enhancements in LDR ("LDR caps") atop $Z_{DR}$ columns were also reported in Bringi et al. (1996, 1997), Jameson et al. (1996), Hubbert et al. (1998), Smith et al. (1999), and Kennedy et al. (2001). Jameson et al. (1996) explained the LDR enhancements by wet frozen drops growing in environments of high cloud water content, whereas Bringi et al. (1997) argued wet growth was not likely in the storms that they investigated. Bringi et al. (1997) and Hubbert et al. (1998) present scattering calculations that demonstrate wobbling freezing raindrops can account for the LDR enhancements without the invocation of wet growth. Hubbert et al. (1998) showed that 30%–40% of the hailstones from the storm they studied had frozen drops as embryos, strongly suggesting the importance of $Z_{DR}$ columns in hail growth. Smith et al. (1999) agreed that freezing of drops is important for the LDR enhancements and as a possible hail embryo source and presented photographic evidence of partially frozen raindrops in an LDR cap, confirming inferences from the polarimetric radar measurements. Kennedy et al. (2001) showed that these LDR caps on $Z_{DR}$ columns preceded the occurrence of hail at the surface.

In addition to hail production, the presence of supercooled liquid and the generation of ice particles play a role in storm electrification. Jameson et al. (1996) pointed out the relation between electrification and the nearly simultaneous appearance of enhanced LDR atop $Z_{DR}$ columns in a sample of small convective storms. Similar observations involving the importance of $Z_{DR}$ columns in electrification and lightning initiation are presented by Goodman et al. (1988), Carey and Rutledge (2000), Bruning et al. (2007), MacGorman et al. (2008), and Woodard et al. (2012). By the turn of the century, observations of $Z_{DR}$ columns became common in single- and multicell convective storms (e.g., Tong et al. 1998; May et al. 2001; Zeng et al. 2001; Cifelli et al. 2002; Knight et al. 2002, 2004; Knight 2006; Evaristo et al. 2010; Rowe et al. 2012) and supercells (e.g., Loney et al. 2002; Ryzhkov et al. 2005b; Scharfenberg et al. 2005; Tessendorf et al. 2005; Kumjian and Ryzhkov 2008; Kumjian et al. 2010; Tanamachi et al. 2012; Kaltenboeck and Ryzhkov 2013; Snyder et al. 2013). The growing recognition of the importance of $Z_{DR}$ columns is reflected in Straka et al. (2000), who created a category for "big drops" in their hydrometeor classification scheme to identify the unusual raindrop size distributions that typify $Z_{DR}$ columns. In addition, practical applications of $Z_{DR}$ columns were discussed by Scharfenberg et al. (2005), who suggest that taller $Z_{DR}$ columns may indicate more vigorous updrafts and present an example of their operational utility. Picca et al. (2010) demonstrate that increases in the horizontal and/or vertical extent of the $Z_{DR}$ column above the 0°C level are positively correlated with increases in low-level $Z_H$ at 10–30-min lag times. Kumjian (2013b) discusses how the height, horizontal extent, and shape of $Z_{DR}$ columns (when viewed in conventional PPI displays) may reveal important information for operational meteorologists. In section 6, we demonstrate quantitatively that $Z_{DR}$ columns do, in fact, carry useful practical information about the storm's behavior and evolution.

b. Simulations of $Z_{DR}$ columns

Using a two-moment bulk microphysics parameterization scheme, Jung et al. (2010) simulated supercell storms in an effort to reproduce commonly observed polarimetric signatures in such storms. Using a three-moment scheme and the same polarimetric radar operator, Snyder et al. (2010) noted that increased CAPE leads to larger $Z_{DR}$ columns. In both cases, however, simulated $Z_{DR}$ columns attained a maximum vertical extent of only 1.5 km above the environmental 0°C level, far short of the 2.5–3.0-km subfreezing excursions often observed in supercells. Part of the discrepancy may be because of the treatment of drop freezing in the microphysics schemes: raindrops freeze instantaneously when cooled to sufficiently low temperatures, at which point they are transferred directly into an ice class (e.g., hail). In reality, freezing of millimeter-sized drops is not instantaneous and can take several minutes (e.g., Pruppacher and Klett 1997; Kumjian et al. 2012).

Use of spectral bin microphysics is more appropriate for studying polarimetric signatures in convective storms. Ryzhkov et al. (2011) present simulated fields of the polarimetric variables from the Hebrew University Cloud Model (HUCM; see below), including a $Z_{DR}$ column. Kumjian et al. (2012) developed a simple one-dimensional bin model of raindrops ascending and freezing in an updraft, explicitly treating probabilistic nucleation and subsequent deterministic freezing of the drops. Despite its simplistic nature, the model successfully reproduced tall $Z_{DR}$ columns and their associated LDR cap and reduced $\rho_{ho}$ at its summit, albeit with smaller magnitudes than typically observed in hail-bearing storms. They also quantified the relationship between $Z_{DR}$ column height and updraft velocity predicted by the model.

c. Summary of previous studies

The consensus in the literature seems to be that $Z_{DR}$ columns comprise large raindrops (resulting from coalescence growth within updrafts) and smaller wet ice
particles. Recirculation of particles into the moisture-rich updraft, although some uncertainty remains on the exact mechanism. Also, a link between $Z_{DR}$ columns and convective storm evolution has been suggested, as well as possible correlative relations between updraft intensity and $Z_{DR}$ column height.

The enhanced polarimetric signatures observed at the summits of $Z_{DR}$ columns (enhanced X-band attenuation, negative $Z_{DR}$, reduced $ho_{hv}$, and/or increased LDR) probably are manifestations of the same types of particles and processes: freezing and frozen drops, and subsequent growth of these particles by accretion and riming. In extreme cases such as supercells, wet growth of hailstones is likely occurring (e.g., Loney et al. 2002; Kumjian and Ryzhkov 2008; Kumjian et al. 2010; Picca and Ryzhkov 2012).

Despite the fact that $Z_{DR}$ columns have been investigated in many studies, many of the details of their development, evolution, and structure remain unclear. To address these problems and the objectives outlined in the introduction, we perform a detailed analysis of $Z_{DR}$ columns using an advanced spectral bin microphysics cloud model, which is described next.

3. Model

This study aims to explore the mechanisms for the formation of $Z_{DR}$ columns, as well as the types and distributions of particles found within them. As seen above, numerical-model investigations of $Z_{DR}$ columns require advanced treatment of the microphysics in deep convective storms. Thus, bulk parameterizations are inadequate for detailed studies of $Z_{DR}$ columns. Because of this fact, we will employ a state-of-the-art spectral bin microphysical model, the HUCM.

The simulations presented in this study include the treatment of “slow freezing” of raindrops by Kumjian et al. (2012), which recently has been implemented in the HUCM and expanded to include collisions (Phillips et al. 2013a,b, manuscripts submitted to J. Atmos. Sci.). The resultant tall $Z_{DR}$ columns produced by the HUCM have a striking resemblance in appearance and evolution to real $Z_{DR}$ columns; thus, we have confidence that the model is reproducing much of the key physics governing $Z_{DR}$ columns and that it is suitable for studying them in detail.

a. HUCM

The HUCM is a 2D, nonhydrostatic spectral bin microphysics model. The microphysics is based on solving a system of equations for size distributions of liquid (one that contains both raindrops and cloud droplets), three types of pristine ice crystals (plates, columns, and dendrites), snow aggregates, graupel, hail, aerosol particles (AP) playing the role of CCN, and a new category of partially frozen or “freezing drops” (more on this below). Each size distribution is discretized into 43 mass-doubling bins, with the smallest bin equivalent to the mass of a liquid droplet of radius 2 $\mu$m. The size of dry AP ranges from 0.005 to 2.0 $\mu$m. The ice nuclei concentration depends on supersaturation with respect to ice as described by the empirical expression of DeMott et al. (2010). Primary nucleation of each ice crystal type occurs within its characteristic temperature range (Takahashi et al. 1991). Secondary ice generation is accounted for during riming (Hallett and Mossop 1974).

Collisions are described by solving the stochastic collection equations for the corresponding size distributions using the Bott (1998) method. Height-dependent, gravitational collision kernels for drop–drop and drop–graupel interactions are from Pinsky et al. (2001) and Khain et al. (2001), and those for collisions between ice crystals are from Khain and Sednev (1995) and Khain et al. (2004). The latter studies include the dependence of particle mass on the ice crystal cross section. Effects of turbulence on collisions between cloud drops are included by using the method of Benmoshe et al. (2012). All collision kernels are modified by a turbulence-induced collision enhancement factor that is calculated using the values of the Taylor microscale Reynolds number and the turbulent kinetic energy dissipation rate at each time step and grid point. As a result, the collision kernels depend on the turbulence intensity and change in time and space.

Time-dependent melting of snow, graupel, and hail as well as shedding of water from hail follows Phillips et al. (2007). We have implemented a new size distribution function of the liquid water mass on or in these hydrometeors that advects and sediments in a way that is similar to that of the mass of the corresponding particles. As a result, these particles are characterized by their total mass and by the mass of liquid water (i.e., the liquid water mass fraction). Thus, the liquid water fraction increases during melting. As soon as it exceeds $\sim$95%–98%, the melting particles are transferred to raindrops.

The treatment of particle freezing recently was substantially improved (see Phillips et al. 2013a,b, manuscripts submitted to J. Atmos. Sci.) relative to that described in Khain et al. (2011) and Ryzhkov et al. (2011). In agreement with theory, two stages of freezing are considered: first is the probabilistic or adiabatic stage, followed by the time-dependent or deterministic stage (e.g., Pruppacher and Klett 1997; Kumjian et al. 2012). The probability of the first stage is described using the parameterization of immersion drop freezing.
proposed by Vali (1994) and the expressions for homogeneous freezing presented by Bigg (1953). Drops with radii below 80 μm that freeze are assigned to plates, whereas larger drops undergoing freezing are assigned to freezing drops. The freezing drops consist of a core of liquid water surrounded by ice. Time-dependent freezing is calculated by solving heat-balance equations that account for the effects of accretion of supercooled drops and ice particles. Both dry growth (when the surface is icy) and wet growth (when the surface is covered by water film) are possible. It is assumed that freezing drops undergoing dry growth collect only supercooled water drops. During wet growth, freezing drops are allowed to collide with other hydrometeors with a collision efficiency equal to 1. If during a collision the freezing drop is larger than its counterpart, the result of the collision is assigned to the freezing-drops category; otherwise, the resulting particle is assigned to the type of the counterpart. Once the liquid water fraction of a freezing drop becomes less than some minimal value (~1%), freezing drops are converted to a hailstone of corresponding mass. When freezing drops encounter higher temperatures and begin to melt, they are transferred to the hail category.

The details of graupel and hail growth (which can be in the dry or wet regime) are also improved significantly by following the approach that is described in Phillips et al. (2013a,b, manuscripts submitted to J. Atmos. Sci.). This improvement includes a treatment of the time-dependent freezing of accreted water by solving heat-balance equations. In addition, smaller hail undergoing dry growth and larger hail undergoing wet growth are separated by calculating a critical radius at each time step. In accord with this, liquid water is allowed in hail and graupel particles at both positive and negative temperatures. Shedding of water in wet growth is also included.

Water accreted onto snowflakes freezes immediately at temperatures below 0°C, where it then contributes to
the rimed fraction. The density of the rimed fraction is assumed to be equal to that of pure ice. This rimed mass distribution advects and sediments in a way that is similar to that of the snow aggregate masses. Rimming mass increases as snowflakes accrete supercooled droplets, leading to an increase in density of the aggregates. The bulk snow density is calculated at each time step for each mass bin. If the bulk density exceeds 0.2 g cm$^{-3}$ (i.e., becomes close to that of graupel), the mass from this bin is transferred to the graupel bin of corresponding mass.
The appearance of water on the surface of hailstones as well as increases in the rimed fraction of snowflakes affects particle fall velocities and coalescence efficiencies. Thus, the collision kernels are recalculated at each time step.

The initial \((t = 0)\) size distribution of CCN is calculated using the empirical dependence of concentration of activated CCN \(N_{\text{CCN}}\) on supersaturation \(S_w\) (%): \(N_{\text{CCN}} = N_0 S_w^m\), where \(N_0\) and \(m\) are the measured constants [for details, see Khain et al. (2000)]. At \(t > 0\), the

Fig. 4. As in Fig. 3, but for the rainwater mass content field (g m\(^{-3}\)).
A prognostic equation for the size distribution of non-activated CCN is solved. Using the value of $S_{w}$ calculated at each time step, the critical radius of CCN particles is determined according to the Köhler theory. The CCN with radii exceeding the critical value are activated, and new droplets are nucleated. The corresponding bins of the CCN size distributions become empty. Note that no giant CCN are used in the simulations, which still produce realistic $Z_{DR}$ columns. Thus, the simulations suggest that $Z_{DR}$ columns may arise in the absence of such giant CCN.

The simulation presented herein is of an intense convective storm observed in southwestern Germany on 28 June 2006. Details of the meteorological conditions of this storm can be found in Noppel et al. (2010) and Khain et al. (2011). In the simulations, the computational area of HUCM was 120 km $\times$ 19 km with horizontal resolution of 300 m and vertical resolution of 100 m. The initial concentration of CCN (at 1\% of supersaturation) was set equal to 3000 cm$^{-3}$.

b. Polarimetric radar operator

The microphysical output of the HUCM is converted into the C-band polarimetric radar variables by using the polarimetric operator of Ryzhkov et al. (2011). Particles are considered as spheroids, with their size distributions explicitly given by the HUCM. Note that the simplified use of smooth spheroids limits our ability to reproduce the observed extrema in $r_{hy}$ and LDR associated with capping signatures. Thus, we restrict our attention to the simulated $Z_{DR}$ columns. Scattering calculations are performed using a combination of Rayleigh formulas and T-matrix computations (e.g., Mishchenko 2000), with relative permittivities that are dependent on
particle type (pure liquid for raindrops, uniform mixtures for melting snowflakes, two-layer spheroids for freezing drops and melting hail, etc.) and the liquid water mass fraction predicted by the model. Other details can be found in Ryzhkov et al. (2011).

4. The origin, life, and death of $Z_{DR}$ columns

The formation of the initial $Z_{DR}$ column in the simulated storm is different from some of the early-stage $Z_{DR}$ columns in developing cumulus clouds that were documented in previous observational studies (e.g., Illingworth et al. 1987, among others). In our simulation, the environment is characterized by a large concentration of aerosols (3000 cm$^{-3}$) and large instability, resulting in a very continental storm. Thus, the initial formation of precipitation-sized particles is delayed because of the smaller initial cloud droplet sizes. Because of this, the first raindrops form within the top portion of the tilted updraft and begin to fall out into weaker updrafts and the compensating downdrafts on its left side (Fig. 2a). Some of these raindrops are recirculated back into the updraft, where they are able to grow quickly by collection of cloud droplets. This process leads to the first appearance of enhanced $Z_{DR}$ (>1 dB) above the 0°C level at about 4.5 km AGL (Fig. 2a). One minute later (Fig. 2b), a vertically extensive column of enhanced $Z_{DR}$ is evident as larger raindrops are growing as they descend through the updraft. By 2700 s into the simulation (Fig. 2c), the presence of melting ice hydrometeors is evident to the left of the rain shaft, and $Z_{DR}$ values continue to increase within the column. It is at this time also that a significant mass of raindrops (>0.5 g m$^{-3}$) has reached the surface. Note the offset between the rain shaft and the enhanced $Z_{DR}$ column. After another minute, $Z_{DR}$ values of greater than 1 dB extend from the ground to nearly 6 km AGL, located at the interface of the rain shaft and the updraft.
Because the simulation considers the continental case with a large CCN concentration (the impacts of aerosols on $Z_{DR}$ columns will be the subject of a future study), the first raindrops form aloft [as in Khain et al. (2013)]. These initial raindrops are small and do not contribute to enhancements in $Z_{DR}$, as seen by the lack of significantly positive $Z_{DR}$ within the rainwater content contours in Fig. 2a. As these drops fall along the cloud edge in weaker updrafts or downdrafts, some are able to penetrate the cloud updrafts, which are characterized by much larger cloud water content. These drops then grow quickly by accretion of cloud water, leading to enhanced $Z_{DR}$ that first appears aloft. Thus, the development of the initial $Z_{DR}$ column begins aloft and grows downward.

Next we consider the development of a mature $Z_{DR}$ column in the presence of hail. Figure 3 provides an overview of the evolution of the simulated $Z_{DR}$ field leading up to such a mature $Z_{DR}$ column. At 10 min prior to the peak column height, the $Z_{DR}$ field shows only small oscillations in height of the melting layer, with a slight depression (indicative of melting of high-density ice particles) at a range of 52–56 km and a slight upward perturbation from about 56 to 60 km. In time, this upward perturbation grows in height and narrows. The $Z_{DR}$ values within this growing column also become larger in time, indicating the growth and fallout of very large drops. By 4680 s, the 1-dB contour has reached nearly 6 km AGL, just shy of 3 km above the environmental 0°C level.

A similar depiction is revealed in the rainwater content field (Fig. 4). The rightmost column of enhanced rainwater content values is associated with the $Z_{DR}$ column. Note that the maximum appears in the middle of the column, centered at heights roughly between 1 and 2 km AGL. Values increase with time as this column becomes more vertically extensive in both the upward and downward directions. This suggests both upward and downward growth of the $Z_{DR}$ column and large drops in this mature-stage $Z_{DR}$ column.

Figure 5 shows example trajectories of small particles originating just below the 0°C level and upshear of the main updraft maximum. Particles with fall speeds below $\approx 1.5 \text{ m s}^{-1}$ that are descending upshear of the updraft core in compensating downdrafts are recycled back into the base of the updraft (Fig. 5a). Note that the trajectories are computed while assuming constant fall speeds. In the real atmosphere, the particles could grow quickly by accretion of cloud water, leading to increased fall speeds and eventual fallout if their fall speed exceeds the vertical air velocity at that height. Indeed, many of the larger raindrops that compose the $Z_{DR}$ column below the 0°C level (Fig. 5b) have grown in this way. Trajectories for particles with larger initial fall speeds are not recirculated but rather fall out beneath the updraft. Starting the trajectories in different initial locations (not shown) results in qualitatively similar results.

Time series of various quantities of interest (Fig. 6) show the evolution of several $Z_{DR}$ columns in the
simulated storm. In each, the height of a given $Z_{DR}$ contour rises and falls over a period of 15–20 min, signifying a life cycle of a $Z_{DR}$ column. Note also that the 1- and 2-dB contours follow very similar evolution, seemingly related to the updraft speed (Figs. 6a,b). This relationship is explored in more detail in section 6. The first $Z_{DR}$ column attains its peak height of 2 km above the environmental 0°C level at about 2820 s into the simulation, when the maximum surface $ZH$ is less than 40 dBZ (Fig. 6c). This also precedes the first occurrence of hail mass at the surface (Fig. 6d). The lagged relation between $Z_{DR}$ column height and surface hail mass content is discussed in section 6.

The life of a $Z_{DR}$ column ends when the $Z_{DR}$ contours descend back to the environmental 0°C level or lower. Such a demise of a mature $Z_{DR}$ column is depicted in Fig. 7, which shows the evolution of the 1.5-dB $Z_{DR}$ contour as well as the $ZH$ of hail. As seen above, the $Z_{DR}$ column attains its peak height by 4680 s (Fig. 7b). At this time, the hail $ZH$ remains less than 60 dBZ throughout the hail column. The first region of hail of greater than 60 dBZ appears near the top of the $Z_{DR}$ column (Fig. 7c) and expands both upward and downward over the next few minutes (Figs. 7d–f). During this period, the $Z_{DR}$ column begins to “collapse,” as is evident by the decreasing height of the 1.5-dB $Z_{DR}$ contour. As the maximum hail $ZH$ increases beyond 70 dBZ (Fig. 7g), what was a $Z_{DR}$ column now begins to invert into a $Z_{DR}$ hole, indicative of large hailstones with intrinsically lower $Z_{DR}$ descending below the melting level. Note that the area of greater than 70 dBZ remains at roughly the same height, extending downward slowly between 4980 and 5100 s, whereas the bottom of the 60-dBZ contour descends to the ground by 5100 s (Fig. 7i).

Despite the demise of the $Z_{DR}$ column depicted in Fig. 7, supercooled raindrops still exist above the

![Fig. 8. $ZH$ from rain only (color shading; dBZ) overlaid with contours of updraft speed (green; 10, 20, and 30 m s$^{-1}$ are shown), total $Z_{DR}$ (magenta contour is 1.5 dB), and $ZH$ from hail (black; 50, 60, and 70 dBZ are shown) for the simulated storm at times (a) 4680, (b) 4860, (c) 5040, and (d) 5220 s.](http://journals.ametsoc.org/doi/pdf/10.1175/JAMC-D-13-0354.1)
melting layer within the updraft. Figure 8 shows the $Z_H$ from raindrops at four times, beginning with the time of peak $Z_{DR}$ column height (4680 s) and continuing through its decay. A striking feature is that the $Z_H$ contribution from rain above the 0°C level remains positive (>20 dBZ) throughout the end of the $Z_{DR}$ column’s life. Thus, hail that is falling through the updraft and the remaining “ghost” of a $Z_{DR}$ column continues to undergo wet growth, leading to the very large $Z_H$ values (>70 dBZ) that are seen in Fig. 7. In contrast, the larger $Z_H$ values from rain descend to the surface throughout this period, leaving behind values of no larger than 45 dBZ above the melting layer. Also of note is the 10 m s$^{-1}$ updraft contour. It initially extends below 3 km, well into an area of rain (Fig. 8a). Throughout the period of $Z_{DR}$ column demise, however, this contour lifts slowly, only extending down to just below 4 km by 5220 s (Fig. 8d). Large raindrops have fall speeds on the order of ~10 m s$^{-1}$. When the 10 m s$^{-1}$ updraft contour extends down into the rain region, these large drops can grow and remain suspended, leading to enhanced $Z_{DR}$.

Once the updraft bubble begins to move upward, the larger drops and hailstones begin to fall out, leading to the collapse of the $Z_{DR}$ column as hail falling from above dominates the $Z_H$. The growth of hail also takes away mass from raindrops as they are collected. This process leads to larger, wetter hailstones that produce very large $Z_H$, dominating the signals from liquid raindrops and partially frozen drops that tend to have larger intrinsic $Z_{DR}$. This suggests that $Z_{DR}$ columns require sufficiently strong updrafts low enough in altitude to “anchor” the column by allowing the growth and lofting of larger raindrops.
5. $Z_{DR}$ column anatomy

In this section, we explore the internal hydrometeor structure of $Z_{DR}$ columns. A snapshot of a mature $Z_{DR}$ column simulated by the HUCM is provided in Fig. 9. Overlaid on the $Z_{DR}$ field are contours of hydrometeor mass content. The highest $Z_{DR}$ values within the column are dominated by rain, with significant hail mass contents located just to the left (upshear) of the $Z_{DR}$ column. Recall that it is particles in this curtain of precipitation that are recirculated into the updraft and contribute to the appearance of the $Z_{DR}$ column. The cloud water content is strongly correlated with updraft speed (not shown); therefore, the $Z_{DR}$ column and region of enhanced rainwater content are offset from the cloud water content and updraft maxima. In the upper portions of the $Z_{DR}$ column, the rainwater content decreases as drops begin to freeze, leading to a localized maximum in freezing-drops mass content at about 4.75-km height, in agreement with the simple model of Kumjian et al. (2012). The freezing drops extend to heights above 6 km, or about 3 km above the environmental 0°C level. As the drops freeze entirely, they are transferred into the hail category, which dominates the hydrometeor mass content above the $Z_{DR}$ column.

Figure 9 also demonstrates the importance of considering the “slow freezing” of raindrops (i.e., having the mixed-phase, freezing-drops category). If raindrops were to freeze instantly, as they are treated in most bulk microphysics schemes used in numerical models, the height of the $Z_{DR}$ column would be reduced by as much as 1 km or more. Instead, the freezing-drops category allows mixed-phase particles with intrinsically larger $Z_{DR}$ to be present at higher altitudes (colder temperatures). The larger $Z_{DR}$ values are possible because of the presence of significant liquid water fractions on freezing drops and hail within the updraft (Fig. 10). The upper portions of the $Z_{DR}$ column have freezing raindrops with large liquid water fraction (>60%). Hailstones falling through the updraft also have large liquid water fractions as they accrete supercooled liquid water drops, particularly in the right half of the column.

In terms of observations, it is the reflectivity factor that governs the appearance of radar signatures and not necessarily the mass of hydrometeors. The $Z_{H}$-dominant hydrometeor type within a limited domain of the $Z_{DR}$ column is shown in Fig. 11. It is clear that hail dominates the upper reaches of the $Z_{DR}$ column as well as the left edge down to about 2 km (i.e., ~1 km below the melting level). Rain dominates much of the column below the melting level as well as the center of the column up to 1 km above the environmental 0°C level. Freezing drops and graupel do not dominate the $Z_{H}$ contribution in any major part of the $Z_{DR}$ column. Freezing drops do contribute to a substantial fraction (up to 30%) of the total $Z_{H}$ (in linear units) in the portion of the column above 4 km AGL, however. Despite not being the dominant contributor, their intrinsically large $Z_{DR}$ (>3 dB; not shown) when associated with large liquid water fractions helps to contribute to the total $Z_{DR}$ enhancement.

Next, we examine the mass distributions of the various hydrometeor species within the mature $Z_{DR}$ column (Fig. 12). At the surface and at 1 km AGL, the mass distributions show the presence of raindrops only, with the distributions being dominated by large (>4 mm) drops. At 2 km AGL, a second peak in the mass distribution appears for tiny droplets (<0.05 mm in diameter); this peak is associated with cloud water mass and is indicative of the presence of an updraft. Between these peaks, the liquid mass contents are much lower, sometimes falling below the plotted scale. At 3 km AGL, the cumulative amount of cloud water mass...
increases, and we see the appearance of some hailstones (<1 cm in diameter). By 4 km, some larger hail is present, along with the appearance of large partially frozen or freezing drops. By 5 km, most of the raindrops of greater than 3 mm in diameter have disappeared from the mass distribution as they begin to freeze, leaving behind substantial masses of both hail and freezing drops. In fact, the maximum in the mass distribution is for freezing drops at this level. Note also that the freezing-drops distribution retains the shape of the raindrops distribution from the lower altitudes, demonstrating that the bulk of the mass of raindrops is being lofted and has begun freezing. At 6 km AGL, very few raindrops of greater than 1 mm in diameter exist, and we see large masses of freezing drops and hailstones (the largest hailstones exceed 2 cm in diameter). Such a progression of the mass distributions with height upward through the $Z_{DR}$ column reveals the lofting, freezing, and subsequent growth of particles.

Figure 13 compares the liquid-drops mass distribution at 4-km height within the mature $Z_{DR}$ column with the distribution just outside the $Z_{DR}$ column. Within the $Z_{DR}$ column, a bimodal mass distribution of liquid drops is evident, indicative of significant mass of both cloud droplets and large raindrops. Just 0.6 km outside the $Z_{DR}$ column, however, the mass distribution is dominated by cloud water, with only minimal contributions from large raindrops except for a peak at around 4–5 mm in diameter. This demonstrates that the particle size distributions may change dramatically over small spatial scales and may be exotic, not conforming to the gamma or inverse exponential type models prescribed a priori in many microphysics parameterization schemes.

We also examine how the particle mass distributions differ from the mature $Z_{DR}$-column stage to the demise stage (Fig. 14). Some weakening of the updraft is inferred from the slight decrease in mass of the larger cloud droplets. In addition, contributions to the mass distribution from the largest raindrops are decreased. The most striking difference is the large increase in the hail mass, particularly for large stones, within the $Z_{DR}$ column during its decay. In fact, the mass distribution of hailstones within the $Z_{DR}$ column during its demise is similar to that in the hail shaft during the mature stage, which is located just to the left of the $Z_{DR}$ column in the simulation, but substantially larger contributions from big hailstones (in excess of 2 cm in diameter) to the mass distribution are present during the $Z_{DR}$-column decay stage. This descent of large hail from aloft marks the demise of the $Z_{DR}$ column, as the contributions to $Z_{H}$

![Figure 11. Reflectivity-dominant hydrometeor class in the $Z_{DR}$ column at 4680 s. Overlaid are the contours of $Z_{DR}$ (0–5 in 0.5-dB increments). Blue corresponds to grid boxes in which rain is the dominant contributor to the $Z_{H}$, red is for hail, purple is for graupel, and yellow is for freezing drops.](image-url)
from the large hailstones dominate the contributions from raindrops, resulting in smaller total $Z_{DR}$ and the eventual disappearance of the column.

6. Practical implications

Previous studies (outlined in section 2) have suggested a relation between the vertical extent of $Z_{DR}$ columns and updraft intensity. Elucidating the relationships between characteristics of the structure and behavior of $Z_{DR}$ columns and storm intensity is important for uncovering any potentially useful prognostic information that $Z_{DR}$ columns may offer. For example, Picca et al. (2010) found that increases in the total volume of $Z_{DR}$ columns above the environmental 0°C level were correlated positively with increases in the surface $Z_H$ on time scales of 20–30 min in a small number of Oklahoma storms. Here, we investigate the relation between $Z_{DR}$ column evolution and meteorologically useful quantities such as the hail content and $Z_H$ at the ground.

The maximum height of the 2-dB $Z_{DR}$ contour is strongly correlated (correlation coefficient $r = 0.93$; Fig. 15a) with the vertical velocity at that height level. Although this result implies that taller $Z_{DR}$ columns are associated with stronger updrafts, we must also consider the geometry of the simulated storms: the maximum updraft speed is almost always located above the $Z_{DR}$ column, and therefore larger heights imply stronger updrafts simply because of the shape of the updraft contours. Perhaps it is best thought that taller $Z_{DR}$ columns are penetrating stronger portions of the updrafts. The correlation between the maximum updraft speed $w_{max}$ in the storm and the height of the 2-dB $Z_{DR}$ contour is weaker but still reveals a slight positive relation ($r = 0.52$; Fig. 15b). When a 2-dB $Z_{DR}$ contour exists above the 0°C level, the height of the 1-dB $Z_{DR}$ contour and $w_{max}$ reveal a positive relation (Fig. 15c), particularly for $w_{max} < 25 \, \text{m} \, \text{s}^{-1}$. The correlation between the 20-dBZ echo-top height and $w_{max}$ is $r = 0.62$ (Fig. 15d).
In a small sample of severe storms, Picca et al. (2010) found that increases in the “$Z_{DR}$ column volume” (defined as the volume of positive $Z_{DR}$ values exceeding a given threshold) above the 0°C level were followed by increases in the ratio of 60- to 40-dBZ areas at low levels, which was used as a proxy for heavy precipitation and hail fall at the surface. In other words, as the $Z_{DR}$ column grew in height and/or areal extent above the 0°C level, increases in the low-level $Z_H$ (and presumably in the presence of hail) followed a short time later. In warm-season, deep convective storms in Oklahoma, this lag was on the order of 20–30 min; in cooler-season, low-topped storms, the lag was shorter. Picca et al. (2010) quantified this relationship by using a lag correlation between the two time series and found peak lag correlations approaching 0.8.

These lag correlations were computed for the time series of various quantities of interest in our simulated storm. Figure 16 shows three such lag correlations. The lag correlation between the height of the 1-dB $Z_{DR}$ contour and the low-level maximum $Z_H$, as well as between the 1-dB $Z_{DR}$ contour height and the low-level maximum hail mass content, show remarkable agreement with the observations in Picca et al. (2010). Both peak at lags of 13–14 min, with peak values $>0.8$. The physical interpretation is that increases in the low-level maximum hail mass content (or maximum $Z_H$) followed an increase in the height of the $Z_{DR}$ column by 13 (14) min.

Also shown in Fig. 16 is the lag correlation between the height of the 20-dBZ echo top and the low-level hail...
Although also displaying a peak correlation of greater than 0.7, the lag is only 9 min. Thus, the simulation strongly suggests that using ZDR column height as a predictive tool has a several-minute advantage over echo top, particularly when providing lead time on hail fall or increased precipitation at the surface. These and other lagged correlations are summarized in Table 1.

Figure 17 compares the simulated lag correlation with that observed during a supercell that occurred on 1 June 2008 in Oklahoma. This storm is selected because it was sampled with a polarimetric WSR-88D in “rapid scan” mode (Kumjian et al. 2010; Dawson et al. 2014). The peak lag correlation is found after about 23 min in the observations (\( r_{\text{lag}} = 0.8 \)), although to facilitate comparison with the HUCM-simulated storm it has been shifted left by 8.8 min. [As shown in Picca et al. (2010), the larger lag time is a function of storm intensity and height; the 1 June 2008 supercell was a much more intense, deep convective storm than the simulated convective storm presented here.] Note the remarkable agreement of the shape and magnitude of the lagged correlation plots. Such large positive lag correlations in both simulations and observations suggest a predictive value of ZDR columns.

Because of the close association between convective storm updrafts and ZDR columns, horizontal cross sections through the ZDR column such as those provided by operational weather radar surveillance scans may provide important information about the properties of the updraft. For example, broad updrafts are known to be conducive to the growth of large hail (e.g., Nelson 1983; Picca and Ryzhkov 2012). Thus, observations of ZDR columns with large cross-sectional area could indicate
the potential for large, damaging hail (e.g., Kumjian 2013b). In a similar way, Kumjian and Ryzhkov (2008) show that the presence of cyclonic vorticity associated with supercell storm updrafts deforms the horizontal cross section of $Z_{DR}$ columns into curved or ringlike shapes. Thus, the cross-sectional shape of $Z_{DR}$ columns as well as their horizontal and vertical extents provide useful information about the potential severity of deep convective storms.

7. Summary

The HUCM used in this study offers a state-of-the-art treatment of microphysics, but it has its own limitations. The main disadvantage of the HUCM used herein is that it is two dimensional. Thus, three-dimensional motions typical of complex storms such as supercells cannot be simulated. On the other hand, the two-dimensional framework allows us to use high spatial resolution that is necessary to simulate microphysical processes. Further, the treatment of microphysical processes is only as good as our empirical and theoretical knowledge of these processes. Some processes (e.g., ice nucleation) for which a well-developed theoretical understanding is lacking are treated as well as one can given the limited knowledge. Despite these limitations, however, the HUCM reproduces realistic polarimetric radar signatures in deep convective storms. This result strongly

<table>
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<th>Peak $r_{lag}$</th>
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<td>9</td>
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suggests that most of the important microphysical processes are adequately represented, at least for the purposes of studying $Z_{DR}$ columns.

The $Z_{DR}$ columns in deep convection are some of the most notable polarimetric radar signatures in such storms. In this paper, we review three decades of observations of $Z_{DR}$ columns and explore their origin, maturity, and demise using the HUCM. In addition to the $Z_{DR}$-column life cycle, the microphysical structure of $Z_{DR}$ columns is also presented, along with some of the practical diagnostic and prognostic information they can provide. In agreement with many of the observational studies reviewed, $Z_{DR}$ columns represent the lofting and growth of large raindrops above the environmental 0°C level. Simulations elucidated the mechanisms for $Z_{DR}$-column formation. The formation of the initial $Z_{DR}$ column is depicted in the schematic in Fig. 18. To start, small raindrops that are grown in the updraft begin to fall out in weaker updrafts at the cloud edge and/or are transported downward in compensating downdrafts. Some of these raindrops are recirculated into the updraft, where they may grow very rapidly through collection of cloud droplets and tiny raindrops ascending from below. Large ($>4-5$ mm) raindrops can grow very rapidly in such conditions and eventually fall out.

FIG. 17. Lag correlation between the height of the 1-dB simulated $Z_{DR}$ contour and the simulated surface maximum $Z_H$ (gray dashed curve), and the lag correlation between the $Z_{DR}$ column volume and low-level $Z_H$ 60/40-dBZ ratio from the 1 Jun 2008 supercell storm in Oklahoma (solid blue curve). The lag correlation plot of the 1 Jun data has been shifted left by 8.8 min to match the time of the peak correlation to facilitate the comparison of shape.

FIG. 18. Schematic illustrating the development of a $Z_{DR}$ column. In each panel, red shading represents updraft regions and blue shading represents downdrafts. (a) Initial growth of cloud droplets via vapor diffusion and coalescence leads to an increase in particle size with height. (b) Lofted small raindrops fall out along the compensating downdrafts on the flank of the updraft. (c) Some of these raindrops are recirculated into the updraft, where they may grow rapidly by collection of cloud water until they are too large and fall out. Other drops that are recirculated into stronger portions of the updraft are lofted and grow, albeit slower.
against the updraft, expanding the \( Z_{\text{DR}} \) column downward from above. In contrast, smaller raindrops and/or those in stronger updrafts are lofted upward where they may also grow by coalescence, forming the subfreezing portion of the \( Z_{\text{DR}} \) column. As the drops ascend to sufficiently cold temperatures, they nucleate and begin to freeze. Because freezing is not instantaneous, these partially frozen drops may exist as long as a few minutes in a vertical layer more than 1 km deep. This layer of mixed-phase particles contributes to reductions in \( \rho_{\text{hv}} \) and enhancements in LDR that have been observed to cap \( Z_{\text{DR}} \) columns in previous studies. If conditions permit, wet growth of these mixed-phase particles will further enhance the capping signatures. Complete freezing and further growth of these lofted particles leads to the production of hail or graupel, depending on in situ growth conditions within the updraft.

Our simulations also demonstrate the demise of \( Z_{\text{DR}} \) columns. Once the updraft core ascends and/or weakens and the hailstones have grown to sizes that are too large to be suspended, they begin to fall out. As they descend through the bottom of the updraft, they encounter the lofted supercooled liquid raindrops. As a result, these wet hailstones dominate the contribution to \( Z_{\text{H}} \) and have intrinsically lower \( Z_{\text{DR}} \) than large raindrops, leading to the demise of the \( Z_{\text{DR}} \) column and, in some cases, an inversion of a column into a \( Z_{\text{DR}} \) hole or hail signature. This column of hail fallout may be shifted downstream (in a storm-relative sense) from the \( Z_{\text{DR}} \) column in cases of vertical wind shear. This leads to the \( Z_{\text{DR}} \) hole being observed next to the \( Z_{\text{DR}} \) column (as in Fig. 1), possibly leading to more persistent or long-lived \( Z_{\text{DR}} \) columns such as those commonly observed in supercell storms.

In mature \( Z_{\text{DR}} \) columns, particle mass distributions are dominated by large raindrops at low levels (i.e., below the environmental 0°C level), in agreement with previous studies. Farther aloft in the \( Z_{\text{DR}} \) column, freezing drops dominate the mass distribution and hailstones become more prevalent with increasing height. During the demise of the \( Z_{\text{DR}} \) column, the mass of larger hailstones (>2 cm in diameter) increases dramatically as they begin to fall through the updraft, leading to a decrease in the total \( Z_{\text{DR}} \) and the shrinking appearance of the \( Z_{\text{DR}} \) column, even if large raindrops are still present in appreciable concentrations (i.e., only the ghost of a \( Z_{\text{DR}} \) column remains).

Important practical applications of \( Z_{\text{DR}} \) columns were found. Positive correlations between \( Z_{\text{DR}} \) column height and the strength of the updraft confirm previous inferences of a physical relation between the two. Thus, the \( Z_{\text{DR}} \) column height may be used as an indicator of the storm’s strength and thus severity. Further, the evolution of the \( Z_{\text{DR}} \) column contains information directly tied to the storm’s behavior. For example, there is a strong positive lagged correlation between the height of the \( Z_{\text{DR}} \) column and the appearance of significant hail mass at the surface. This suggests great promise for the use of \( Z_{\text{DR}} \) columns as prognostic tools for the onset of hail at the surface in severe convective storms. The lagged correlations for \( Z_{\text{DR}} \) columns are larger and offer more lead time than other indicators of storm behavior such as \( Z_{\text{H}} \) echo top.

With the emergence of dual-polarization radars in the United States and around the world, we strongly advocate the use of \( Z_{\text{DR}} \) columns for operational and research applications. Only one dual-polarization radar can be used to identify the updraft location and provide some information about its strength. Changes in the appearance of \( Z_{\text{DR}} \) columns can give forecasters a prognosis of storm behavior and may improve the lead time for warnings of hail and increases in storm severity. The \( Z_{\text{DR}} \) columns may also aid in tracking dominant updrafts in multicell storms or storm-merger situations. Future studies will undoubtedly uncover novel applications and uses for \( Z_{\text{DR}} \) columns.

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