Simulations of Polarimetric, X-Band Radar Signatures in Supercells.  
Part II: $Z_{DR}$ Columns and Rings and $K_{DP}$ Columns

JEFFREY C. SNYDER  
Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma, and NOAA/OAR/National Severe Storms Laboratory, and School of Meteorology, University of Oklahoma, Norman, Oklahoma

HOWARD B. BLUESTEIN  
School of Meteorology, University of Oklahoma, Norman, Oklahoma

DANIEL T. DAWSON II  
Purdue University, West Lafayette, Indiana

YOUNGSUN JUNG  
Center for Analysis and Prediction of Storms, Norman, Oklahoma

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ABSTRACT

A high-resolution numerical model and polarimetric forward operator allow one to examine simulated convective storms from the perspective of observable polarimetric radar quantities, enabling a better comparison of modeled and observed deep moist convection. Part I of this two-part study described the model and forward operator used for all simulations and examined the structure and evolution of rings of reduced copolar cross-correlation coefficient (i.e., $\rho_{hv}$ rings). The microphysical structure of upward extensions of enhanced differential reflectivity ($Z_{DR}$ columns and $Z_{DR}$ rings) and enhanced specific differential phase ($K_{DP}$ columns) near and within the updrafts of convective storms serve as the focus of this paper. In general, simulated $Z_{DR}$ columns are located immediately west of the midlevel updraft maximum and are associated with rainwater lofted above the $0^\circ$C level and wet hail/graupel, whereas $Z_{DR}$ rings are associated with wet hail located near and immediately east of the midlevel updraft maximum. The deepest areas of $Z_{DR} > 1$ dB aloft are associated with supercells in the highest shear environments and those that have the most intense updrafts; the upper extent of the $Z_{DR}$ signatures is found to be positively correlated with the amount and mean-mass diameter of large hail aloft likely as a by-product of the shared correlations with updraft intensity and wind shear. Large quantities of rain compose the $K_{DP}$ columns, with the size and intensity of the updrafts directly proportional to the size and depth of the $K_{DP}$ columns.

1. Introduction

Part I of this study (Snyder et al. 2017, hereinafter Part I) describes the polarimetric radar forward operator and modeling configuration for the simulations that are studied herein, and quasi-circular or arclike areas of reduced copolar cross-correlation coefficient at lag zero (i.e., $\rho_{hv}$ rings) in simulated supercells were examined. The same simulations described in Part I are used herein to examine vertically oriented regions of enhanced differential reflectivity (i.e., $Z_{DR}$ columns and rings) and specific differential phase (i.e., $K_{DP}$ columns) above the $0^\circ$C level. The reader is referred to Tables 1 and 2 in Part I for details on the numerical model, forward operator, and model configuration.

Analyses of polarimetric radar data have indicated the presence of columns of relatively high $Z_{DR}$ above the environmental $0^\circ$C level in thunderstorms (e.g., Hall et al. 1984; Illingworth et al. 1987; Tuttle et al. 1989; Meischner et al. 1991; Conway and Zrnić 1993; Holler et al. 1994; Brandes et al. 1995; Brinig et al. 1996, 1997; Zrnić and Ryzhkov 1999; Kennedy et al. 2001; Loney et al. 2002; Kumjian and Ryzhkov 2008, hereinafter KR08; Kumjian et al. 2010, 2014; Kumjian 2013; Homeyer and...
The part of a thunderstorm’s updraft between the level of free convection and the equilibrium level possesses positive thermal buoyancy, by definition, and is characterized by a positive temperature perturbation relative to the surrounding environment. As a result, assuming the updraft extends through the environmental 0°C height, the local 0°C level will be perturbed upward by the updraft (and, as a result of evaporation and/or melting, perturbed downward by the downdraft); we would then expect that there would be raindrops within the updraft above the environmental 0°C level.

When raindrops rise in the updraft and enter a subfreezing environment, they do not freeze instantly—depending upon temperature, drop size, and nucleation characteristics, it may take several minutes for a raindrop to freeze (e.g., Johnson and Hallett 1968; Smith et al. 1999), during which time it may continue to rise in the updraft (e.g., Kumjian et al. 2012). As a result, the buoyant updraft carries liquid water drops to an altitude above that of both the environmental and perturbed/local 0°C level (e.g., Musil et al. 1976; Brandes et al. 1995; Brinigi et al. 1996). Further, in the presence of a convective updraft, the smaller drops (which have lower terminal fall speeds) tend to be advected upward more quickly than do the larger drops; the effect of size sorting in an updraft preferentially leaves larger raindrops lower in the updraft as the smaller drops advect more quickly to higher altitudes. Since $Z_{DR}$ is often largest for large raindrops and near 0 dB for small drops and pseudorandom oriented scatterers (e.g., tumbling hail and graupel), the lofted raindrops and mixed-phased particles within the updraft tend to result in a local maximum in $Z_{DR}$ within the updraft; the enhanced $Z_{DR}$ within the updraft can extend well above the 0°C level in what is termed the $Z_{DR}$ column. Since rain and/or mixed-phase hydrometeors like wet hail likely compose $Z_{DR}$ columns, the presence of very large hail (for which $Z_{DR}$ tends to be relatively low while $Z_H$ tends to be high) within the updraft can mask the $Z_{DR}$ column (e.g., Kumjian et al. 2014); $Z_{DR}$ tends to be relatively low while $Z_H$ tends to be high in large hail, so the reflectivity-weighted $Z_{DR}$ for a mixture of rain and hail would tend to be closer to that of the hail than that of the rain.

Using trajectory and polarimetric analyses in a dual-Doppler analysis of a Colorado hailstorm, Conway and Zrnić (1993) noted that an observed $Z_{DR}$ column was located just west of the center of the updraft (and left of the shear vector) and consisted of raindrops and wet hydrometeors. Other in situ observations support the notion that the $Z_{DR}$ column is nearly coincident with the updraft (e.g., Brinigi et al. 1991; Brandes et al. 1995).

The $Z_{DR}$ columns simulated by Kumjian et al. (2012, 2014) and Snyder et al. (2015) were composed of 1) raindrops (at the base of the $Z_{DR}$ columns), 2) raindrops in the process of freezing as they advected upward within the updraft (in the middle and upper sections of the columns), and 3) wet hail and previously melting hail that were recirculating within the updraft (in the upper and upshear parts of the columns). Snyder et al. (2015) describe an algorithm designed to identify and quantify $Z_{DR}$ columns in operational weather radar data with the potential use of aiding assessments of convective storm evolution and structure.

Like $Z_{DR}$ columns, an upward extension of enhanced $K_{DP}$ has been observed to extend above the environmental 0°C height near or within the updraft of supercells (e.g., Hubbert et al. 1998; Zrnić and Ryzhkov 1999; Loney et al. 2002; KR08; Romine et al. 2008; Kumjian et al. 2010; Snyder et al. 2013; Homeyer and Kumjian 2015; van Lier-Walqui et al. 2016). The $K_{DP}$ in frozen hydrometeors tends to be small (e.g., <1 km$^{-1}$ at S band and <3° km$^{-1}$ at X band) in the absence of appreciable resonance effects (e.g., Straka et al. 2000; Kennedy and Rutledge 2011; Thompson et al. 2014; Oue et al. 2016), although it can be higher (e.g., up to ~8° km$^{-1}$) in hail at X band (Dolan and Rutledge 2009). Raindrops lofted in the updraft above the environmental 0°C level and, where delayed nucleation and noninstantaneous drop freezing produce supercooled liquid water, above the local 0°C level contribute to $K_{DP}$ columns either directly (as in a large amount of liquid water) or indirectly (by creating favorable conditions for wet growth of ice). In Loney et al. (2002) and Schlatter (2003), the $K_{DP}$ column was primarily composed of a large number of mixed-phase hydrometeors. Hubbert et al. (1998) suggested that the significant liquid water content that composed an observed $K_{DP}$ column may have resulted from liquid shed by hail falling at the periphery of the updraft. Although many such drops can be present, Loney et al. (2002) found that shed drops were not directly responsible for the $K_{DP}$ in a different supercell because such drops were too small to contribute meaningfully to enhanced $K_{DP}$; instead, it was the abundant wet/mixed-phased hydrometeors that dominated scattering in the $K_{DP}$ column.

Previous observations of supercells (e.g., Loney et al. 2002; Zrnić and Ryzhkov 1999; KR08; Romine et al. 2008; Kumjian et al. 2010; Snyder et al. 2013) have noted a spatial separation between $Z_{DR}$ and $K_{DP}$ columns. The two convective storms examined by Zrnić et al. (2001) both had $Z_{DR}$ and $K_{DP}$ columns; the first was a severe hailstorm (the authors did not indicate whether or not it was a supercell) in which there was large overlap between the $Z_{DR}$ and $K_{DP}$ columns,
whereas, in the second (a nonsupercell “ordinary” storm), the columns were coincident with one another. In cases in which there is an offset, the $K_{DP}$ column is often located on the left flank of the updraft to the west and northwest of the $Z_{DR}$ column, and it is often, though not always (e.g., Loney et al. 2002; KR08), associated with the maximum in $Z_{H}$. Similar to $Z_{DR}$ columns, $K_{DP}$ column location, depth, and volume appear to be generally proportional to updraft location, intensity, and size (e.g., van Lier-Walqui et al. 2016).

Although nearly the entirety of past studies on the polarimetric structure of supercells and convective storms utilized data collected using S- or C-band radars, Snyder et al. (2013) presented some examples of $Z_{DR}$ and $K_{DP}$ columns in supercells observed by an X-band radar. For illustrative purposes, we present in Fig. 1 an example of these signatures observed during the summer of 2015 while the mobile rapid-scan X-band polarimetric radar known as “RaXPol” (Pazmany et al. 2013) was collecting hemispheric range–height indicator (RHI) scans. A strong convective storm was approaching from the west (where range values in Fig. 1 increase toward the west). “Attenuation corrected” $Z_{H}$ and $Z_{DR}$ indicate an upward extension of $Z_{DR} > 1$ dB (i.e., a $Z_{DR}$ column) associated with an area of 50–60 dBZ $Z_{H}$ aloft. An upward extension of enhanced $K_{DP}$ (e.g., exceeding $4^\circ$ km$^{-1}$) is identified near and to the west of the $Z_{DR}$ column as well. In both the $Z_{DR}$ and $K_{DP}$ columns, $\rho_{hv}$ is less than $\sim 0.93$ (and is less than 0.85 near the top of the $Z_{DR}$ column). A nearby sounding (not shown) showed the 0°C level to be near 4.0 km AGL, which is corroborated nicely by the melting layer signature seen in the radar data (i.e., shallow layer of reduced $\rho_{hv}$, with positive perturbations apparent in $Z_{DR}$ and $Z_{H}$ to the east of the radar near ranges from $-4$ to $-6$ km). As such, identifiably enhanced $Z_{DR}$ associated with the $Z_{DR}$ column extends $\sim$ (2–3) km above the environmental 0°C level in this particular scan.

In addition to $Z_{DR}$ columns, KR08 point out circular or semicircular structures of enhanced $Z_{DR}$ above the environmental 0°C level. The features, referred to as $Z_{DR}$ rings by KR08, may be full rings encircling an updraft or only partial rings; examples of $Z_{DR}$ rings observed at X band can be seen in Figs. 14, 17, and 18 in Snyder et al. (2013). When the $Z_{DR}$ rings are incomplete (i.e., partial rings), they are positioned on the inflow side of the updraft (KR08; Payne et al. 2010). Other than what has been mentioned in a very limited number of papers (e.g., KR08; Payne et al. 2010; Kumjian et al. 2010; Snyder et al. 2013), little has been written about $Z_{DR}$ rings. It is not entirely clear if the microphysical composition of $Z_{DR}$ columns and $Z_{DR}$ rings are the same and if the latter are just spatially deformed variations of the former. As discussed by Kumjian et al. (2010), $Z_{DR}$ rings can originate when graupel (and, presumably, hail) falling along the right flank of the updraft undergoes wet growth in the presence of a large amount of liquid water in the updraft. At temperatures above 0°C, melting graupel and hail with high water fractions may support enhanced $Z_{DR}$ in these ring- or arc-shaped areas.

As mentioned in Part I, our analyses focus primarily on simulated radar fields at X band. There are an ever-increasing number of X-band polarimetric weather radars in use, and the majority of past studies that looked at polarimetric signatures in supercells used data from S-band radars. The scattering characteristics of hydrometeors can vary significantly as a function of radar wavelength on account of resonance effects associated with non-Rayleigh scattering (e.g., Atlas et al. 1960). For example, hail is often associated with much higher $Z_{H}$ (e.g., $\sim$ 15 dBZ for some sizes) at S band than at X band (e.g., Atlas and Ludlam 1961; Dolan and Rutledge 2009; Snyder et al. 2010). Meaningful differences between a given signature at S and X bands will be noted where applicable, but the majority of the discussion will pertain to X band.

The purpose of this paper is to examine the microphysical and kinematic characteristics of $Z_{DR}$ columns and rings and $K_{DP}$ columns in supercells simulated by a high-resolution numerical model using advanced three-moment bulk microphysics. Specific details regarding the model and forward operator can be found in Part I. Since comparisons of polarimetric signatures with the kinematic and microphysical fields from a single simulation may be dubious, with large uncertainty about the generality of the results, we instead ran eight 3-h simulations. The simulations use the same thermodynamic sounding, but each has one of eight hodographs as shown in Fig. 3 of Part I; each simulation is identical except for the initial wind profile. There are two hodograph lengths for each of the four different “shapes” of hodographs, with simulations named according to the shape and length of hodograph used (15r10, 25r10, 15r10_057, 25r10_057, 15q10, 25q10, 15str, and 25str). Although we highlight notable differences and similarities among the different simulations as appropriate, this paper is not intended to provide a detailed examination of the specific effect of the wind shear on simulated polarimetric fields. Rather, the different

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1 Since the actual attenuation (and differential attenuation) are not known exactly, we are only able to estimate the amount of attenuation and differential attenuation. These estimated amounts are added to the observed $Z_{H}$ and $Z_{DR}$ to arrive at an estimate of the attenuation-corrected $Z_{H}$ and $Z_{DR}$. 2 Since the actual attenuation (and differential attenuation) are not known exactly, we are only able to estimate the amount of attenuation and differential attenuation. These estimated amounts are added to the observed $Z_{H}$ and $Z_{DR}$ to arrive at an estimate of the attenuation-corrected $Z_{H}$ and $Z_{DR}$. 3 Since the actual attenuation (and differential attenuation) are not known exactly, we are only able to estimate the amount of attenuation and differential attenuation. These estimated amounts are added to the observed $Z_{H}$ and $Z_{DR}$ to arrive at an estimate of the attenuation-corrected $Z_{H}$ and $Z_{DR}$. 4 Since the actual attenuation (and differential attenuation) are not known exactly, we are only able to estimate the amount of attenuation and differential attenuation. These estimated amounts are added to the observed $Z_{H}$ and $Z_{DR}$ to arrive at an estimate of the attenuation-corrected $Z_{H}$ and $Z_{DR}$. 5 Since the actual attenuation (and differential attenuation) are not known exactly, we are only able to estimate the amount of attenuation and differential attenuation. These estimated amounts are added to the observed $Z_{H}$ and $Z_{DR}$ to arrive at an estimate of the attenuation-corrected $Z_{H}$ and $Z_{DR}$. 6 Since the actual attenuation (and differential attenuation) are not known exactly, we are only able to estimate the amount of attenuation and differential attenuation. These estimated amounts are added to the observed $Z_{H}$ and $Z_{DR}$ to arrive at an estimate of the attenuation-corrected $Z_{H}$ and $Z_{DR}$.
FIG. 1. Hemispheric RHI scan through a convective storm sampled by a mobile RaXPol (Pazmany et al. 2013) during the overnight hours of 26 Jun 2015 in eastern Kansas showing attenuation-corrected $Z_H$, attenuation-corrected $Z_{DR}$, $K_{DP}$, and $\rho_{hv}$. Positive-range values are westward; negative-range values are eastward. The black outline in all panels marks the approximate top of the main $Z_{DR}$ column (although high differential attenuation may mask the actual top, particularly along the right side of the image); a possible second, much smaller $Z_{DR}$ column is marked by the dashed black curve in the $Z_{DR}$ panel. Attenuation has been estimated using the ZPHI method (Testud et al. 2000); differential attenuation has been estimated using a linear relation between specific attenuation and specific differential attenuation valid in rain. Undercorrection of attenuation and, in particular, differential attenuation is apparent in the upper-right part of the top two panels. Range resolution is 75 m, with range gates spaced every 30 m.
hodographs are used primarily to expand the sample size in an effort to enhance confidence in the results.

The three-moment scheme described in Milbrandt and Yau (2005, hereinafter MY3), which includes six hydrometeor species [rain (r), snow (s), graupel (g), hail (h), ice crystals (i), and cloud water (c)], is used for all simulations. Polarimetric radar fields discussed in this paper are obtained by use of a polarimetric radar forward operator (PRFO; Jung et al. 2010) with diagnostic water fraction (including the bulk fractional water $f_w$, of species $x$, or $f_wx$; Dawson et al. 2014); other quantities noted are directly predicted by or derived from the numerical model and microphysics scheme (e.g., mean-mass diameter of species $x$, or $D_{max}$ and gamma distribution shape parameter $\alpha$).

As noted in Part I, the PRFO has considerable influence on the calculated radar fields owing to a number of a priori relations (e.g., the shape–aspect ratio relationship and the canting angle variability–mass water fraction relationship) that must be specified because the microphysics scheme does not provide all of the information needed to calculate the radar fields. This is particularly true for mixed-phase hydrometeors, which the microphysics scheme does not predict at all yet which compose or affect, to varying degrees, the signatures examined herein. That the PRFO is able to simulate the signatures (to varying levels of accuracy, perhaps) indicates that it, with the included diagnostic water method, is at least somewhat effective in mitigating the deficiencies of the microphysics.

As in Part I, the effects of attenuation and non-horizontal elevation angles are not included in the results presented in this paper since both add dimensions to the parameter space and can significantly complicate analysis.

2. Simulated $Z_{DR}$ columns and rings

This section addresses two signatures observed in the simulated $Z_{DR}$ field—$Z_{DR}$ columns and $Z_{DR}$ (half) rings (referred to as rings, although they are often more like curved bands or partial rings). In most simulations, these two signatures are spatially distinct with different microphysical compositions, although both are characterized by significantly positive $Z_{DR}$ above the 0°C level within and near the updraft of the simulated storm. It is not known if these two signatures are as discrete in “real world” supercells as they are in the simulations, however, or whether limitations of the microphysics cause the simulated signatures to be more distinct than they actually are in nature.

a. Kinematic and microphysical composition

The maximum heights of $Z_{DR}$ $> 1$ dB in columns above each horizontal grid point for a selected time ($t \sim 5040$ s) for each simulation reveal the general shape of the $Z_{DR}$ columns (Fig. 2) associated with the cyclonic supercells produced in each simulation; such a product is similar to the output of the algorithm described in Snyder et al. (2015). Note that the 0°C temperature in the initial sounding used to set up these simulations is $\sim 3800$ m AGL. The tendencies that will be discussed momentarily generally hold at other times in each simulation as well, though there is more variability in some simulations than in others. In general, the straight-line hodographs (15str and 25str) produced $Z_{DR}$ columns that were oriented elliptically along the shear vector, whereas the curved hodographs tended to have more cylindrically shaped $Z_{DR}$ columns. The 15r10 and 15r10_057 simulations produced $Z_{DR}$ columns oriented primarily in the north–south direction, with a distinct narrowing on the north side of the column. The $Z_{DR}$ columns tended to be considerably larger in the “strong” shear cases than in the “weak” shear cases (e.g., cf. left and right columns of Fig. 2). As would be expected given the hodographs used in this study, simulations using the curved hodographs produced a dominant cyclonic supercell, whereas simulations using the straight hodographs produced quasi-symmetric, splitting supercells. The $Z_{DR}$ columns in both of the straight hodographs and in all of the weak shear simulations tended to be relatively unsteady, with “pulselike” behavior, whereas the $Z_{DR}$ columns in the other strong shear simulations (particularly 25q10) tended to be steadier.

The maximum height of the $Z_{DR}$ columns is very similar (approximately 5350–5600 m AGL) in most simulations at most times; the height of the $Z_{DR}$ columns is 1500–1800 m above the environmental 0°C height for most simulations except 25r10_057 (in which the $Z_{DR}$ column extends $> 2200$ m above the environmental 0°C level), which is approximately 500–800 m above the 0°C level of a surface-based parcel lifted through the level of free convection (as with parcel theory).

Although there were differences in the sizes and shapes of the $Z_{DR}$ columns between the different simulations, the microphysical composition of the simulated $Z_{DR}$ columns was similar in all runs. In general, the $Z_{DR}$ columns were located to the west of the center of maximum vertical velocity in the updrafts. One example, consistent with $Z_{DR}$ columns from other simulations, is selected from the 25r10 simulation (Fig. 3). The peak updraft speed at this height is 39 m s$^{-1}$. The $Z_{DR}$ column, marked by the red arrow in Fig. 3a, becomes less distinct above this height. The air temperature within the $Z_{DR}$ column at this height is $\sim 269 \text{K} \left( -4 \text{°C} \right)$; Fig. 3b), and the $Z_{DR}$ column is spatially associated with $q_i$ exceeding 4 g kg$^{-1}$ and $D_{min} \sim 1$–1.5 mm (Fig. 3c). The column contains relatively small hail (e.g., $D_{mh} < 4$ mm; Fig. 3d).
FIG. 2. The maximum height (m) of X-band $Z_{DR}$ > 1 dB at $t = 5040$ s in the (a) 15r10, (b) 25r10, (c) 15r10_057, (d) 25r10_057, (e) 15q10, (f) 25q10, (g) 15str, and (h) 25str simulations. The spatial scale in all panels is identical. The grids for each simulation are translated to keep the primary cyclonic supercell near the center of the domain. The black arrow in (a) points to a $Z_{DR}$ column; the red contours mark the areas where enhanced $Z_{DR}$ is found above the initial environmental 0°C level.
with $q_h$ of 2–4 g kg$^{-1}$ (Fig. 3e); the hail is wet (i.e., $f_{wh} > 50\%$) and is characterized by a relatively broad size distribution (i.e., $a_h < 2$). There is very little graupel present in the $Z_{DR}$ column at this height. As will be discussed later, there is a distinct difference in the microphysical characterization of the area of enhanced $Z_{DR}$ marked by the red arrow (which is being labeled as part of the $Z_{DR}$ column) and that by the yellow arrow (which will be labeled as part of the $Z_{DR}$ ring). A scatterplot of $Z_{DR}$ versus $D_{mb}$ shown in Fig. 3f clearly reveals these two regimes of enhanced $Z_{DR}$; the area of lower $D_{mb}$ but higher $f_{wh}$ and $D_{mr}$ is associated with the $Z_{DR}$ column near the center of the updraft, whereas the area of higher $D_{mb}$ but lower $f_{wh}$ and $D_{mr}$ characterizes those areas that are along the eastern edge of the updraft.
The vertical structure of the simulated Z_{DR} columns is better illustrated using vertical cross sections. In a south–north cross section through the supercell in the 25r10 simulation shown in Fig. 4, an upward extension of Z_{DR} > 3 dB can be seen up to ~5600 m AGL. This Z_{DR} column is contained within the updraft, where upward vertical velocities range from ~10 m s^{-1} to more than 45 m s^{-1}. Enhanced Z_{DR} of 3–5 dB characterizes the Z_{DR} column at both S (Fig. 4a) and X (Fig. 4b) bands; enhanced K_{DP} (e.g., 4^\circ–6^\circ km^{-1} at X band; Fig. 4c) is found along the northern side of the updraft and Z_{DR} column. A slight increase in Z_{DR} is also seen near the top of the column where very wet hail is indicated (f_{wh} > 80%; Fig. 4d). At S band, the Z_{DR} column is considerably narrower than it is at X band, with an area of reduced Z_{DR} at S band along the northern (right) side of the column below ~5 km (white arrow in Fig. 4a). The narrower Z_{DR} column at S band is the result of the presence of a small amount of wet, small-to-medium-sized hail [i.e., f_{wh} ~ 30\%–40\%, D_{mh} ~ 5–15 mm (Fig. 4d), and q_b < 1 g kg^{-1} (Fig. 4e)], which reduces S-band Z_{DR} but negligibly affects X-band Z_{DR}. Since the total Z_{DR} is reflectivity weighted, it is less sensitive to large hail at X band because, on account of (non-Rayleigh) resonance effects, Z_H from large hail is generally lower at X band (relative to that at S band). Consequently, in a rain–hail mixture, large hail contributes less to Z_{DR} at X band than it does at S band. Presumably a result of size sorting (which is more accurately captured by the triple-moment MY3 scheme used in this study than by other single- or double-moment schemes), much of the Z_{DR} column is associated with enhanced D_{mr} (i.e., 2.0–3.5 mm; Fig. 4e).

Some of the simulations also show well-defined partial Z_{DR} rings along the eastern periphery of the midlevel updraft of the simulated supercells (e.g., the yellow arrow in Fig. 3a); these areas of enhanced Z_{DR} are consistently separated in space from the Z_{DR} columns discussed above, although the two features occasionally “connect” at altitudes between the environmental and updraft-perturbed 0°C levels. In such cases, the western part of the combined Z_{DR} enhancement is associated with high q_r and moderate q_h and q_g, whereas the eastern part is generally associated with very low q_r, q_h, and q_g. The Z_{DR} rings at generally high altitudes appear as curved bands of enhanced Z_{DR} usually located in the southeastern periphery of the updrafts (i.e., the right-forward part when viewed along the storm motion vector) and arc around the east side of the updrafts. Such rings are seen most prominently in the 15q10 and 25q10 simulations, although they are also produced in the 25r10_057 and 25r10 simulations; the other simulations generally produce only intermittent and less distinct Z_{DR} rings. Stronger updrafts were, in general, associated with more prominent Z_{DR} rings. The 1800–9000-s average of the peak w was higher in the right-moving supercells that produced the most prominent Z_{DR} rings (i.e., approximately 41, 43, 47, and 48 m s^{-1} in the 25r10, 15q10, 25q10, and 25r10_057 simulations, respectively) than in those simulations that did not produce such Z_{DR} rings (i.e., approximately 35, 37, 39, and 40 m s^{-1} in the 25str, 15str, 15r10_057, and 15r10 simulations, respectively).

The hydrometeor and radar characterization of the Z_{DR} rings in the simulations is different from that associated with the “primary” Z_{DR} columns noted above. In the Z_{DR} rings, q_r and q_b are low (i.e., <1 g kg^{-1}; Figs. 3c,e), and since they extend considerably above the Z_{DR} columns, the minimum air temperature within the Z_{DR} rings tends to be considerably lower. Within and around a Z_{DR} ring is a similarly shaped band of large hail (e.g., D_{mh} ~ 1–2 cm; Fig. 3d) that is characterized by a narrower size distribution (a_{h} ~ 3–5) than seen in the surrounding areas. The maximum magnitude of the Z_{DR} within the ring is ~2 dB and occurs where D_{mh} ~ 11 mm (Fig. 3e). In general, differences in the Z_{DR} rings and columns are evident in the bivariate normalized histograms of various parameters using data within Z_{DR} rings and columns from all simulations and all times (Fig. 5). Although there is not a clear difference in Z_{H} between the columns and rings, there are more marked differences in f_{wh}, D_{mh}, and p_{hv}, as indicated by the gray (representing data within Z_{DR} columns) and red (representing data within Z_{DR} rings) arrows in Figs. 5b–d. From a radar standpoint, the Z_{DR}–p_{hv} histogram (Fig. 5d) delineates the two Z_{DR} features comparatively well.

The appearance of Z_{DR} columns and rings is strongly affected by whether or not the microphysics scheme and forward operator can simulate mixed-phased hydrometeors. In fact, the Z_{DR} rings are not produced at all when the diagnostic water fraction routine is turned off. This sensitivity highlights the need to treat mixed-phased hydrometeors properly when polarimetric quantities are calculated using a polarimetric radar forward operator, and it presents an additional source of error when interpreting the simulated polarimetric characteristics of these features given uncertainties in diagnosing liquid water fractions. The Z_{DR} rings produced in these simulations often extend several kilometers above the Z_{DR} (and K_{DP}) columns, with some rings starting at lower altitudes (e.g., 4500–5000 m AGL) but most starting near the top of the Z_{DR} columns. The microphysical structure of the top of the rings is quite similar to that at lower altitudes, though there tends to be more graupel present at the higher altitudes. For example, Fig. 6 contains selected fields from the 25r10 simulation at a height of ~6500 m AGL.
FIG. 4. (a) S-band $Z_{DR}$ (dB), (b) X-band $Z_{DR}$ (dB), (c) X-band $K_{DP}$, (d) $f_{wh}$ (%), (e) $D_{mr}$ (mm) with $q_v$ (g kg$^{-1}$; contoured in gray), and (f) $D_{mh}$ (mm) with $q_v$ (g kg$^{-1}$; contoured in gray) along a south–north cross section through the updraft of the cyclonic supercell in 25-10 at 7320 s. Black contours in all panels are $w$ (m s$^{-1}$) and are marked every 10 m s$^{-1}$; red contours in (a) and (b) represent the 263- and 273-K isotherms. The pink and white arrows in (a) highlight the $Z_{DR}$ column and the downward protrusion of low $Z_{DR}$ adjacent to the $Z_{DR}$ column, respectively.
or near the upper extent of a $Z_{DR}$ ring; these plots are representative of what is seen in the other simulations. The area of enhanced $Z_{DR}$ contoured in black in Fig. 6a is located along the eastern extent of the warm thermal perturbation associated with the updraft. Winds within the $Z_{DR}$ “ring” are primarily directed toward the warmer temperatures within an area of horizontal convergence. Although the total mass concentrations of graupel, hail, and rain in this area are small ($q_g$, $q_h$, and $q_r < 0.4$ g kg$^{-1}$; Figs. 6b–d), the rainwater that does exist at this height is located with $D_{mh}$ of 3–8 mm and $f_{wh}$ up to $\sim 25\%$ in the same area where $Z_{DR}$ exceeds 2 dB. Whereas there is typically more hail than graupel in the primary $Z_{DR}$ column, there is nearly as much (if not slightly more) graupel as there is hail in this $Z_{DR}$ ring. Despite this, the graupel is considerably smaller than the hail is (e.g., $D_{mg} \sim 1$ mm) and contributes less to the $Z_{DR}$ enhancement. Past studies have suggested that $Z_{DR}$ may be enhanced by hail or graupel falling into the warm updraft and melting (partially or completely; e.g., KR08; Conway and Zrnić 1993), but this process does not appear to be the main cause of the $Z_{DR}$ half ring shown here because this feature is seen primarily at subfreezing temperatures ($T \sim -13^\circ$C) where melting is not occurring. Rather, in this case, it appears that the $Z_{DR}$ ring is associated with the advection of hail into the periphery of the updraft where it undergoes wet growth in the presence of supercooled liquid water. Kumjian et al. (2010) hypothesized the same general process for the $Z_{DR}$ rings examined in their study. However, this does not preclude the possibility that ice at lower levels (i.e., at above-freezing temperatures) that began to melt was
advected into the updraft and is now rising to the height shown here, similar to what is discussed in Conway and Zrnić (1993). Regardless, the signature is indicative of the presence of wet ice particles.

Most prominent ZDR rings were produced by the simulations that had the strongest midlevel storm-relative winds as determined from observed storm motions and the hodographs associated with the background environment (Fig. 4 in Part I). It seems as though the stronger midlevel storm-relative winds increased the advection of hail (falling outside or at the periphery of the updraft) toward the core of the updraft where supercooled water was present. Those simulations with weaker storm-relative midlevel winds generally were associated with less overlap between large hail and supercooled water inside the forward and right (relative to the shear vector) edge of the updraft.

A vertical cross section through the updraft of the supercell in the 25q10 simulation is shown in Fig. 7 to illustrate some of the differences in the microphysical composition of a simulated ZDR column and ring. Here, we use characteristics of the predicted hydrometeor quantities to infer the processes occurring where these features are found; we will soon examine the microphysical tendencies (i.e., sources and sinks) resulting from the processes modeled within the MY3 scheme (which are not typically provided as output from the model/scheme). The main ZDR column (Fig. 7a) is

FIG. 6. From the 25r10 simulation at $t = 7320$ s—(a) $T$ (color shading; K), $Z_{DR}$ at X band (black; contoured every 1 dB), and $w$ (gray; contoured every 10 m s$^{-1}$) with wind vectors plotted every 800 m; (b) $D_{mg}$ (color shading; mm) and $q_g$ (white; contoured every 2 g kg$^{-1}$, starting at 1 g kg$^{-1}$); (c) $D_{mh}$ (color shading; mm), $f_{wh}$ (black; contoured every 10%), and $q_h$ (white; contoured every 2 g kg$^{-1}$ starting at 1 g kg$^{-1}$); and (d) $D_{mr}$ (color shading; mm), $Z_{DR}$ (black; contoured every 1 dB), and $q_r$ (white; contoured at 0.1 g kg$^{-1}$). The height of the $w$ data is ~6400 m; the height of all other data is ~6500 m.
located primarily west of the most intense part of the updraft (generally west of the 80-km mark on the abscissa) and extends ~1800 m above the environmental 0°C level and approximately 600–800 m above the locally perturbed 0°C level. It is composed of rainwater with high rain reflectivity (z_r) and hail reflectivity (z_h; Fig. 7b). At the top of the column, q_r decreases with height, and q_h increases with height (Fig. 7c); we infer that rain is freezing into hail within the updraft or that rain is being collected by (and subsequently frozen on) hail or graupel. Given the low D_mr near the top of the Z_{DR} column, the enhanced Z_{DR} appears to be attributable to wet hail; the hail near the top of the Z_{DR} column is very wet (f_{ab} > 60%), as is the graupel (not shown). A substantial maximum in the total number concentration of raindrops (N_{T,r}; Fig. 8a) in this same region is evidence of drop shedding during wet growth of hail. Note that, in the MY3 scheme, shed drops are assumed to have a D_mr of 1 mm; if this assumption is poor or invalid in naturally occurring supercell updrafts, Z_{DR} from the simulated supercells may deviate from that observed in nature. Meanwhile, the area of enhanced Z_{DR} aloft associated with the Z_{DR} ring (near and east of the 80-km mark on the abscissa) has a much different microphysical structure. This feature is located near the eastern edge of the updraft and is characterized by modest z_r (e.g., 10–30 dBZ) and D_mr < 1 mm up to ~9 km AGL. There is a relatively narrow overlap between this lofted
supercooled rainwater and an overhanging area of hail (Fig. 7b); $q_r$ is generally below 2 g kg$^{-1}$ (Fig. 7c), $q_r$ is generally below 0.5 g kg$^{-1}$ (Fig. 7c), and $D_{mh}$ is up to 14 mm (Fig. 7d). This narrow zone of $Z_{DR}$ up to 4 dB along the eastern periphery of the updraft appears to be the result primarily of scattering by a limited amount of wet, relatively large hail undergoing wet growth.

The characteristics of the size distributions in the areas we have labeled as the $Z_{DR}$ column and the $Z_{DR}$ ring may provide insight into why the ring is much taller than the column. The rain that is lofted to greater heights near and east of the center of the updraft and ends up contributing to the $Z_{DR}$ rings generally has smaller $D_{mr}$ (i.e., <1 mm) and $q_r$ than the part of the updraft associated with the $Z_{DR}$ column (e.g., where $D_{mr}$ is 1–3.5 mm). Experiments on the freezing of water droplets (e.g., Pitter and Pruppacher 1973) indicate that the median freezing temperature for a population of liquid drops increases as drop size increases (i.e., small drops tend to freeze at colder temperatures relative to larger drops). As noted in the model of freezing drops reported by Kumjian et al. (2012), drop size distributions (DSDs) with a smaller $D_{mr}$ experience delayed freezing relative to those with a larger $D_{mr}$ because the rate at which nucleation occurs at a given temperature is proportional to the volume of the raindrop (Bigg 1953); although smaller drops freeze more quickly once nucleation begins, fewer small drops (relative to large drops) will nucleate per unit time so that, in effect, the process of freezing does not begin until the smaller drops are higher in the updraft. In addition, the median nucleation rate is affected by the rate of cooling (Bigg 1953), which is proportional to the speed at which drops rise in the updraft; at higher cooling rates (i.e., stronger updrafts), nucleation occurs at colder temperatures. Consequently, it may not be surprising that the area of

**Fig. 8.** An east–west vertical cross section through the updraft in the 25q10 simulation at 6000 s showing (a) $N_{Tr}$ (color shading; m$^{-3}$), $q_c$ (contoured in black every 2 g kg$^{-1}$), and $w$ (contoured in white every 10 m s$^{-1}$); (b) $N_{Tg}$ (color shading; m$^{-3}$), $q_g$ (contoured in black every 2 g kg$^{-1}$), and $f_{wg}$ (contoured in white every 20%); and (c) $N_{Th}$ (color shading; m$^{-3}$), $q_h$ (contoured in black every 2 g kg$^{-1}$), and $f_{wh}$ (contoured in white every 20%).
the updraft where the rain distribution is skewed toward smaller drops can loft rainwater to colder temperatures and higher heights (as in the $Z_{DR}$ ring) relative to those areas where $D_m$ is larger (such as in the $Z_{DR}$ column). In addition, $N_{Tg}$ (Fig. 8b) and $N_{Tq}$ (Fig. 8c) are much higher near the top of and above the primary $Z_{DR}$ column than within the narrower area near the axis of the updraft (where rainwater is found up to ~9 km), likely indicating the creation of new graupel and hail particles; rainwater appears to be depleted more quickly via collection by the more abundant hail and graupel particles at the top of the $Z_{DR}$ column relative to the area along and east of the updraft axis.

To provide evidence for the above analysis, we turn to the actual hydrometeor sources and sinks that are used in the MY3 scheme but that are not typically available as model output. In this scheme, rainwater can be removed through several processes, including probabilistic freezing (Bigg 1953) and collection–accretion by ice species (i.e., hail, graupel, snow, or cloud ice); the latter is also referred to as three-component freezing since the outcome of the collision of rain and one of the frozen species can result in a particle of the same or different frozen species (depending upon the bulk density of the combined hydrometeor). Through the lower and middle sections of the $Z_{DR}$ column examined in Fig. 9 ($t$ = 6000 s in the 25q10 simulation—the same as shown in Figs. 9 and 10), there is net collection of rainwater by hail (Fig. 9a; i.e., QCLrh $> 0$ g kg$^{-1}$). Near the top of the $Z_{DR}$ column between approximately 5000 and 5400 m (i.e., above the 0°C isotherm), though, there is negative rainwater collection by hail, which is the result of drop shedding produced during the wet growth of hail (Fig. 9c; QSHHr $> 0$ g kg$^{-1}$). Above ~5400 m (i.e., near the top of the $Z_{DR}$ column), there is again net positive collection of rainwater by hail. Interestingly, more rainwater is being removed through collection by graupel (Fig. 9e) near the top of the column than through collection by hail, presumably because of the additional creation of new drops during wet growth of hail. Meanwhile, none of the rainwater within the main $Z_{DR}$ column is being lost through probabilistic freezing (Fig. 9g). When normalized by total $q_r$ (as in the right column of Fig. 9), it is apparent that much (25%–30% during the previous time step) of the rainwater at the top of the $Z_{DR}$ columns is lost through collection by graupel, with lesser amounts collected by hail along the right side of the $Z_{DR}$ column where $q_h > q_g$ (Fig. 10). Again, much of the rain mass is coming from shedding from wet growth of hail, which, considering MY3 assumes diameters of 1 mm for shed drops, appears to contribute to the reduction in $Z_{DR}$ at the top of the $Z_{DR}$ column.

The $Z_{DR}$ columns described herein are shallower than some of those observed in nature and simulated by other researchers using spectral bin microphysics (e.g., Kumjian et al. 2014; Snyder et al. 2015). As noted previously, $Z_{DR}$ column height was inversely proportional to the median drop size in the model results reported in Kumjian et al. (2012). Bulk schemes tend to produce rain too quickly in an updraft, perhaps on account of insufficiencies in the autoconversion of cloud droplets to raindrops (e.g., Cotton 1972; Cotton and Anthes 1989; Straka and Rasmussen 1997; Straka 2009). If rain is produced too early/too low within an updraft, it is possible that the rain would have a larger median diameter than is found in nature, resulting in a shorter $Z_{DR}$ column owing to earlier freezing. Although this makes sense from a physical point of view, it is worth noting that, in our simulations, it is the collection of water by graupel and hail that is responsible for removing rain at the top of the $Z_{DR}$ column. However, the issue of “rain too early and low” that is addressed by Straka and Rasmussen (1997) and others may give rise to more rapid initiation of hail (and graupel), which in turn acts to collect (i.e., deplete) the rain and limit $Z_{DR}$ column height.

Unlike commonly used bulk schemes, the bin scheme used in Kumjian et al. (2012, 2014) and Ilo Koviz et al. (2016) accounts for the noninstantaneous nature of drop freezing by using time-dependent freezing, tracks/ prognoses water fraction, and has a “freezing drops” category that captures drop freezing more accurately than available bulk schemes can (Phillips et al. 2014, 2015). We ran a couple of preliminary simulations using the three-moment Ziegler variable density (ZVD) scheme (Ziegler 1985; Mansell et al. 2010; Dawson et al. 2014), and the $Z_{DR}$ columns in those simulations were deeper than those produced by using the MY3 scheme. The specific sensitivity of the microphysics scheme to simulated $Z_{DR}$ columns (and other polarimetric signatures) is not the focus of this research, but it warrants further investigation.

Given the sensitivity of the polarimetric variables to the accurate representation of mixed-phased precipitation, predicting water fraction or continuing development of diagnostic water fraction methods may improve the polarimetric structure of simulated convective storms. The diagnostic mass water fraction method used in this study reallocates mass from rain to the ice particles (e.g., hail and graupel) in an effort to simulate mixed-phased precipitation. Whereas the model can only predict a mixture of dry ice and rain, such a mixture seems unlikely in nature (at least in deep convective storms); where raindrops coexist with ice in convective storms (e.g., in areas of melting snow, hail, and graupel or wet growth of hail), it seems more likely that the ice would be wet. This method maintains the
FIG. 9. Selected microphysical mass tendencies from the 25q10 simulation valid at 6000 s, as shown by mass concentration change (over the previous 5-s time step; g kg$^{-1}$) of (a) rainwater collected by hail (QCLrh; positive represents a decrease in rainwater), (c) rainwater shed from hail (QSHhr; positive represents an increase in rainwater), (e) rainwater collected by graupel (QCLrg; positive represents a decrease in rainwater), and (g) rainwater via probabilistic freezing (QFZrh; positive represents a decrease in rainwater). The red curve represents the 0°C isotherm. (b),(d),(f),(h) The tendencies normalized by $q_r$. 

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FIG. 10. RaXPoL, a mobile radar, sampling a supercell on the evening of 11 May 2014 in southwestern Kansas. The (a) $Z_H$ (dBZ), (b) $Z_{DR}$ (dB), and (c) $K_{DP}$ ($^\circ$ km$^{-1}$) (left) reconstructed vertical cross sections and (right) data collected at 18° elevation angle. Height and range distances are in kilometers. The white and red outlines in (b) mark the possible locations of two features similar to the $Z_{DR}$ column and half ring.
mean-mass diameters of all distributions, which means that the \( Z_{\text{DR}} \) of the rain is essentially unaffected. However, \( Z_{\text{DR}} \) of the reconstructed mixed-phased hydrometeors (e.g., wet hail) generally increases because the addition of liquid water onto the surface of hail and graupel 1) increases the effective dielectric constant of the hydrometeors, 2) generally decreases the aspect ratio (i.e., the particles become more oblate), and 3) narrows the width of the canting angle distribution. Although this diagnostic water method aims to improve the polarimetric radar representation of the simulated convective storms by mitigating deficiencies in the underlying microphysics scheme, its use adds another source of error and brings forth additional sensitivities (e.g., to a priori relations in the forward operator) that affect the calculated radar variables. Diagnosing water fraction may not be advisable in all situations, but given the lack of mass water fractions predicted by nearly all bulk microphysics schemes and given the importance of properly treating mixed-phased hydrometeors when simulating polarimetric radar fields, it seems to be a worthwhile endeavor given the alternative (i.e., not allowing mixed-phase hydrometeors).

As noted previously, in the simulations performed for this study, \( Z_{\text{DR}} \) (half) rings appear to be associated with hail falling along the periphery of the updraft or being brought into the updraft on storm-relative winds that have a component toward the updraft and growing as it encounters supercooled water in the updraft. This characterization of \( Z_{\text{DR}} \) (half) rings is essentially the same as that discussed in Kumjian et al. (2010). An examination of the individual hydrometeor tendencies indicates that no substantial evaporation is occurring in this area, so dry air entrainment, which preferentially evaporates the smallest drops first, thereby enhancing \( Z_{\text{DR}} \) (which KR08 hypothesized for one possible explanation of \( Z_{\text{DR}} \) rings), is not the cause of the \( Z_{\text{DR}} \) rings produced in these simulations. Instead, there is rainwater collection by hail and graupel, with a small amount of rainwater being generated through drop shedding from wet growth. In addition, the simulated \( Z_{\text{DR}} \) rings are not associated with melting hail or graupel because temperatures are below 0°C.

Secondary regions of enhanced \( Z_{\text{DR}} \) above \( Z_{\text{DR}} \) columns akin to the \( Z_{\text{DR}} \) rings examined herein were not found in the simulations detailed by Kumjian et al. (2014) and Snyder et al. (2015). However, those simulations were only two dimensional; the more complicated three-dimensional microphysical and kinematic structures observed with supercells were not captured. Some \( Z_{\text{DR}} \) rings that have been described in the literature may just be \( Z_{\text{DR}} \) columns that have been deformed by changes in the structure/shape of the parent updraft. Regardless, there may be hints of two such features in data collected by RaXPoI. On the evening of 11 May 2014, RaXPoI sampled a supercell in southwestern Kansas. Reconstructed RHI plots through the rear flank of the supercell reveal a bounded weak echo region (BWER; e.g., Chisholm 1973) in \( Z_{\text{DR}} \) (Fig. 10a). A \( Z_{\text{DR}} \) exceeding 4 dB is evident along the periphery of the BWER, including along the east/forward side (purple box in Fig. 10b) where \( Z_{\text{DR}} \) is less than 25 dBZ; enhanced \( Z_{\text{DR}} \) is also evident to the west–rear of the BWER (white box in Fig. 10b), where \( Z_{\text{DR}} \) is considerably higher (e.g., 30–50+ dBZ). The \( K_{\text{DP}} \), which tends to be a good proxy for rainwater content, indicates the possibility of large rainwater contents on the rear side of the BWER and limited rainwater content on the forward side of the BWER (Fig. 10c). This is quite similar to Figs. 9 and 10, wherein areas of enhanced \( Z_{\text{DR}} \) aloft downshear of the updraft are found to be associated with 1) relatively high rainwater contents (\( Z_{\text{DR}} \) column) along the western edge of the updraft and 2) relatively low rainwater contents (\( Z_{\text{DR}} \) half ring) along the eastern and southeastern edge of the updraft. Unfortunately, RaXPoI did not collect data above 5–6 km altitude, so the top of the observed \( Z_{\text{DR}} \) enhancements is not known.

b. Bulk correlations

Numerous kinematic and microphysical quantities were examined during the course of the analysis to assess relationships between the radar signatures and convective storm structures and properties. The relationships soon to be discussed were calculated within subdomains that were fixed during the duration of each simulation and were chosen such that the primary supercell always remained while other convective storms did not. However, storm splits and other convective storm “debris” separate from the primary supercell still occurred in the subdomains and are reflected in the statistics presented. Consequently, despite efforts to mitigate this, the analysis contains the effects of more than just the primary supercell, and thus, correlation coefficients are expected to be lower than they otherwise would be if only the primary supercell of interest were examined exclusive of any other convective storm element.

Since the \( Z_{\text{DR}} \) column marks the upward protrusion of rainwater (and/or wet hail) within the updraft above the 0°C level, one could posit that the size of the \( Z_{\text{DR}} \) column should vary directly with the size of the updraft. Observations (e.g., Kumjian et al. 2010; van Lier-Walqui et al. 2016) generally support this, as do the simulations examined in this paper. A scatterplot of updraft area and \( Z_{\text{DR}} \) area at 5350 m AGL for all simulations (Fig. 11a) reveals the direct relation between updraft size and \( Z_{\text{DR}} \).
column size, although the actual correlation coefficients vary in each simulation. For example, in the 25q10 simulation, the $r$ between the area of $w > 5\text{ m s}^{-1}$ near the environmental $0^\circ\text{C}$ level and the area of $Z_{DR} > 1\text{ dB}$ near the top of the $Z_{DR}$ column is $\sim 0.90$. In general, the strong shear hodographs were associated with considerably stronger and larger updrafts and larger $Z_{DR}$ columns. The former is consistent with Giangrande et al. (2013), who found a positive but weak correlation between updraft size and intensity, and Kirkpatrick et al. (2009), who found that increasing shear leads to larger and more intense updrafts in simulated convective storms. The correlations between $Z_{DR}$ column size and updraft area in the weak shear simulations are lower, but subjective assessments of the data indicate that the associations are being strongly affected by convective storm elements outside of the primary supercell updraft.

Even so, the overall $r$ (using data for all simulations and all times) between $Z_{DR}$ column size and updraft area in the weak shear simulations are lower, but subjective assessments of the data indicate that the associations are being strongly affected by convective storm elements outside of the primary supercell updraft. The horizontal extent of the rain field aloft is also positively correlated with the horizontal area of the $Z_{DR}$ column (Fig. 11b). The strong shear simulations generally produced larger volumes of $q_r > 1\text{ g kg}^{-1}$ aloft and larger $Z_{DR}$ columns. Overall, the magnitudes of $r$ between the areas of $q_r > 1\text{ g kg}^{-1}$ and $Z_{DR} > 1\text{ dB}$ near the top of the $Z_{DR}$ columns for many of the simulations were generally above 0.50.

In addition to having wider updrafts and more expansive areas of rainwater aloft, supercells in the strong shear simulations generally produced more hail [similar to the tendency seen in Dennis and Kumjian (2017)] and generally had more hail near the top of the $Z_{DR}$ columns. There was also a tendency for more large hail aloft with the deeper $Z_{DR}$ columns; the correlation in this case likely is not indicative of a cause-and-effect relation as both deeper $Z_{DR}$ columns and a larger amount of large hail aloft are likely with the stronger and larger updrafts (which increase updraft mass flux). Even still, the relation between $Z_{DR}$ column depth and large hail aloft is suggestive of a potential application of $Z_{DR}$ columns for operational meteorologists.

Aggregating all simulations, there was a weak but discernible trend in the maximum height of the $Z_{DR}$ columns with changes in updraft area; weaker updrafts tended to be associated with slightly shallower $Z_{DR}$ columns. The trend for increasingly deep $Z_{DR}$ columns with increasing updraft intensity was apparent but not robust in all simulations. In general, however, the relationship between updraft intensity and maximum $Z_{DR}$ height was stronger for the strong shear cases than it was for the weak shear cases. For example, there was a strong correlation between maximum $Z_{DR}$ height and maximum $w$ at $5600\text{ m AGL}$ in the (Fig. 12a) 25r10 and 25r10_057 simulations (Fig. 12b). This relationship fits the current understanding of $Z_{DR}$ columns and rings (e.g., Snyder et al. 2015).

Some correlation coefficients were not high at zero lag time but increased at nonzero lag times. One such example is the relationship between the area of $D_{mh} > 25\text{ mm near ground}$ and the $Z_{DR}$ column as measured by
both the area (at ~5350 m AGL) and the maximum height of the ZDR column. In several of the simulations, there was a distinct peak in r at a lag time of approximately 10–20 min. Time series of these quantities from the 25r10_057 simulation are presented in Fig. 13. The local maximum in r (~0.4) occurred at a lag of ~18 min; in other words, changes in ZDR column height and area (at ~5350 m AGL) preceded changes in the area of Dmh > 25 mm near ground level by 15–20 min. This makes some physical sense if we consider that an increase in the intensity of the updraft can be expected to be associated with an increase in the height and size of the associated ZDR column. All other things being equal, hail is likely to grow larger within this intensified updraft, and this hail will eventually fall to the ground. The periodicity of the variability in ZDR column height and large hailfall at the ground results in positive correlations at lag times indicative of large hail preceding ZDR column height changes. However, we argue that a physical cause and effect in this case (i.e., more large hail at the ground causes an increase in the ZDR column) is less likely than in the opposite scenario (i.e., ZDR column height changes precede more large hail at the ground) because the ZDR column tends to respond more quickly to updraft changes than does the occurrence of large hail near the ground (which we would intuitively expect to lag updraft changes). Also note the negative correlation observed at a lag time of 0 min, which was also found in three of the four cases examined in Picca et al. (2010) using radar observations of supercells. A similar but stronger lag-time relationship between characteristics of the ZDR column and the occurrence of large hail near the ground was observed by Picca et al. (2010) and Kumjian et al. (2014); the correlations in this study may have been weaker owing to the simpler treatment of hail used herein relative to that used by Kumjian et al. (2014).

3. Simulated KDP columns

In the range of raindrop sizes for which the Rayleigh approximation is appropriate, KDP is proportional to approximately drop diameter D_4.2 (Sachidananda and Zrnić 1986), indicating that it is generally a better proxy for q_r (which is proportional to ~D^3) than is z (which is generally proportional to D^6). Since hail tends to tumble as it falls (e.g., Knight and Knight 1970), it can be thought of as being relatively spherical from a scattering standpoint, and combined with the reduced relative dielectric constant (e_r) of hail relative to that of liquid water, it tends to be characterized by KDP of less than 3°km^{-1} at X band (although hailstones that are water coated have particular oblateness and/or produce strong resonance scattering may result in large KDP). Consequently, KDP has been used for rainfall estimates in place of ZH (e.g., Zrnić and Ryzhkov 1996), and one typically expects the spatial structure of the KDP field to resemble the q_r field for typical DSDs. Our simulations tend to produce KDP and ZDR columns in similar locations and with similar shapes (e.g., cf. Fig. 2 and Fig. 14). The primary geospatial difference between the two is the smaller extent of enhanced KDP aloft relative to enhanced ZDR aloft. The ZDR rings previously examined are not associated with enhanced KDP, which is not surprising given the low q_r associated with the ZDR rings. The simulated KDP columns tend to be centered slightly west (i.e., upshear) of the ZDR columns. The straight hodographs (15str and 25str) are associated with zonally elongated KDP columns, and the more highly curved hodographs tend to produce more
cylindrically shaped $K_{DP}$ columns consistent with the general shapes of the updrafts in each simulation.

Two representative examples of $K_{DP}$ columns are shown in east–west vertical cross sections from the 25q10 and 15q10 simulations (Fig. 15). Maxima in $K_{DP}$ and $q_r$ are located along the western side of the updraft and are generally displaced slightly west of the primary $Z_{DR}$ column (Figs. 15a,c). For the most part, $K_{DP}$ tends to be directly proportional to $q_r$, particularly where $q_h$ is limited (Figs. 15b,d). The enhancement of $K_{DP}$ at the top of the column is associated with an increasing number of small-to-moderate hailstones (e.g., $D_{mh}$ of 2.5–4 mm) with significant water fraction (e.g., $f_{wh}$ generally 40%–80%). In addition, the total number concentration of rain is maximized in this same region (very similar to that seen at a later time in Fig. 8a), the result of drops shed from wet growth of hail and from wet graupel. A scatterplot of the data from Fig. 15 shows that $K_{DP}$ increases as $q_r$ increases, particularly where $q_h$ is low (Fig. 16); locations at which $K_{DP}$ tends to deviate appreciably from a relatively linear trend with $q_r$ generally have higher $q_h$.

Aggregating all simulations between 1800 and 9000 s, $K_{DP}$ column area (i.e., where $K_{DP}$ > 1 dB km$^{-1}$ aloft) was positively correlated with various measures of the amount of hail in the parent storm. For example, the cross-sectional area of $K_{DP}$ columns near the 0°C level (i.e., ~3800 m AGL) and the total amount of hail at higher altitudes (e.g., 5350–5600 m AGL) were correlated with $r > 0.70$. The area of the $K_{DP}$ column at 5350
FIG. 14. As in Fig. 2, but showing the maximum height of \( K_{DP} > 5 \) km\(^{-1} \) for the simulations. The red contours mark the areas where the \( K_{DP} \) column extends above the initial, environmental \( 0 \)°C level.
and 5600 m AGL was strongly correlated with total rainwater at those heights (i.e., $r = 0.94$ and 0.86, respectively). Correlation coefficients between $K_{DP}$ column cross-sectional area near 3800 m AGL and the area of $w > 15$ m s$^{-1}$ (at various levels between 3500 and 5600 m AGL) exceeded 0.65; the size of the $K_{DP}$ column at higher altitudes (e.g., ~5350 m AGL) was more highly correlated with maximum $w$ between 3500 and 5600 m AGL (where $r$ ranged from 0.58 to 0.60). In general, the correlations between the characteristics of $K_{DP}$ columns and the aforementioned updraft and precipitation quantities were higher for the strong shear simulations than for the weak shear simulations. These relationships are supported by observational evidence such as that provided by van Lier-Walqui et al. (2016), who, in studying convective storms sampled by C- and S-band radars during a field campaign in the central United States, found that $K_{DP}$ column size was a good proxy for updraft mass flux and was correlated with the coverage of very heavy rainfall.

The general tendency for larger $K_{DP}$ columns with larger and more intense updrafts is a relationship shared
with $Z_{DR}$ columns. Indeed, the correlation coefficients between the cross-sectional areas of $K_{DP}$ and $Z_{DR}$ columns at any given level generally were at least 0.65. In addition, the maximum height of the $K_{DP}$ columns were well correlated (e.g., $r = 0.78$) with the maximum height of the $Z_{DR}$ columns. From an observational perspective, because of the wavelength dependence of $K_{DP}$ (i.e., $K_{DP}$ is higher at X band than at S band) and more severe differential attenuation, $K_{DP}$ columns may be better than $Z_{DR}$ columns for identifying updrafts at X band.

4. Summary and conclusions

To examine the composition and characteristics of $Z_{DR}$ columns, $Z_{DR}$ rings, and $K_{DP}$ columns, eight idealized, high-resolution numerical simulations were studied using a three-moment bulk microphysics scheme coupled to a polarimetric radar forward operator. The simulations had identical thermodynamic initial states, but they had different (horizontally homogeneous) wind profiles. In general, the strong shear simulations were associated with supercells with the widest and tallest $Z_{DR}$ columns and rings. In many of the simulations, there were two distinct regions of $Z_{DR} > 1 \text{ dB}$ above the 0°C height. A primary $Z_{DR}$ column was typically associated with low (on the east and north sides) $q_r$ lofted within and immediately west of the center of the updraft. In most simulations, this rainwater was depleted through collection by graupel and hail near 5600 m AGL ($\sim 1800 \text{ m above the environmental 0°C level and } \sim 1000 \text{ m above the local 0°C level}$). Local temperatures at this height were approximately $-5^o$ to $-7^o$C, which is not as cold as more sophisticated modeling using spectral bin microphysics that better capture time-dependent freezing have shown (Kumjian et al. 2012, 2014; Snyder et al. 2015; Ilotoviz et al. 2016). In the future, modifications to the rain-to-hail parameterizations may be considered to slow the freezing of drops to account for the noninstantaneous nature of drop freezing (e.g., Phillips et al. 2007, 2015). In addition, prognosing water fraction instead of diagnosing it afterward from separate hydrometeor species may better capture the microphysical fields within and near the top of the $Z_{DR}$ columns.

The second region of enhanced $Z_{DR}$ aloft appeared to be very similar to observed $Z_{DR}$ rings (e.g., KR08; Payne et al. 2010; Kumjian et al. 2010; Snyder et al. 2013). In nearly all cases, the $Z_{DR}$ rings were incomplete rings located near the center of and along the forward side of the updraft. These rings typically extended to considerably greater heights than did the primary $Z_{DR}$ columns associated with high $q_r$ within the updraft. The rings occurred where relatively low $q_r$ was superimposed on low $q_h$, and the rings were nearly collocated with a local maximum in $D_{mh}$. In general, the stronger shear simulations produced more prominent $Z_{DR}$ rings; the most prominent $Z_{DR}$ rings were associated with supercells in the 25q10, 15q10, 25r10_057, and 25r10 simulations, which happen to be the simulations with the highest 0–3-km storm-relative helicity and generally highest 1–5-km AGL updraft helicity and updraft velocities. Such an association is not surprising—the stronger low-level shear in the aforementioned soundings resulted in more robust mesocycones and a stronger upward-directed vertical perturbation pressure gradient force that yielded more intense updrafts, a result that is supportive of previous literature (e.g., Brooks and Wilhelmson 1993). Owing to resonance effects, the $Z_{DR}$ rings were more apparent at X band than at S band.
Combining all simulations, $Z_{DR}$ column size tended to be proportional to updraft size, and the maximum height of $Z_{DR} > 1$ dB showed some positive relationship to updraft intensity, particularly in the strong shear cases. This finding suggests that monitoring the evolution of the $Z_{DR}$ column may be an effective way by which one can assess the evolution of the updraft and corroborates some of the conclusions of Kumjian et al. (2014) and Snyder et al. (2015).

The spatial extent of the rain and hail fields aloft was found to be positively correlated with the extent of the $Z_{DR}$ columns and rings. In some of the simulations, there was a relative maximum in the correlation between the number of grid points with $D_{mh} > 25$ mm at 120 m AGL and the maximum height of $Z_{DR} > 1$ dB at a lag time $\sim 20$ min, albeit with $r < 0.5$, suggesting that examining the evolution of the $Z_{DR}$ column may allow one to anticipate large hail at the surface with a positive lead time. These results corroborate those discussed in Picca et al. (2010) and Kumjian et al. (2014).

As with $Z_{DR}$ columns, the width of $K_{DP}$ columns was proportional to the sizes of the updrafts within the simulated supercells. The $K_{DP}$ column sizes were best correlated with $Z_{DR}$ column sizes, updraft intensity, the amount of rainwater aloft, and the amount hail in the storm. The maximum height of $K_{DP}$ columns was most strongly correlated with the maximum 1–6-km AGL updraft helicity. The simulated $K_{DP}$ columns tended to track the $q_e$ field very well, which agrees with the prior expectation. Most $K_{DP}$ columns were located west of the center of the updrafts and were centered slightly west of the $Z_{DR}$ columns. There was enhanced $K_{DP}$ near the top of the $K_{DP}$ columns associated with wet hail and graupel. In general, since wet hail and graupel affected $K_{DP}$ band more than it did at S band, the use of $K_{DP}$ as a proxy for $q_e$ or rain rate may not be straightforward at X band if mixed-phase hydrometeors are present.

In general, results of this study are consistent with previous studies and observations, which lends credibility to the microphysics scheme and forward operator. Although in situ verification of microphysics schemes in simulated supercells is difficult owing to challenges in characterizing the three-dimensional hydrometeor distribution, the use of polarimetric radar forward operators can allow users and designers to evaluate model results using real-world observations (e.g., Dawson et al. 2014). This should serve as motivation for continued development of advanced forward operators that can be used for model evaluation.

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