Modeling and Interpretation of S-Band Ice Crystal Depolarization Signatures from Data Obtained by Simultaneously Transmitting Horizontally and Vertically Polarized Fields

J. C. HUBBERT, S. M. ELLIS, AND W.-Y. CHANG

National Center for Atmospheric Research, Boulder, Colorado

S. RUTLEDGE

Colorado State University, Fort Collins, Colorado

M. DIXON

National Center for Atmospheric Research, Boulder, Colorado

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ABSTRACT

Data collected by the National Center for Atmospheric Research S-band polarimetric radar (S-Pol) during the Terrain-Influenced Monsoon Rainfall Experiment (TiMREX) in Taiwan are analyzed and used to infer storm microphysics in the ice phase of convective storms. Both simultaneous horizontal (H) and vertical (V) (SHV) transmit polarization data and fast-alternating H and V (FHV) transmit polarization data are used in the analysis. The SHV $Z_{dr}$ (differential reflectivity) data show radial stripes of biased data in the ice phase that are likely caused by aligned and canted ice crystals. Similar radial streaks in the linear depolarization ratio (LDR) are presented that are also biased by the same mechanism. Dual-Doppler synthesis and sounding data characterize the storm environment and support the inferences concerning the ice particle types. Small convective cells were observed to have both large positive and large negative $K_{dp}$ (specific differential phase) values. Negative $K_{dp}$ regions suggest that ice crystals are vertically aligned by electric fields. Since high $|K_{dp}|$ values of 0.8 km$^{-1}$ in both negative and positive $K_{dp}$ regions in the ice phase are accompanied by $Z_{dr}$ values close to 0 dB, it is inferred that there are two types of ice crystals present: 1) smaller aligned ice crystals that cause the $K_{dp}$ signatures and 2) larger aggregates or graupel that cause the $Z_{dr}$ signatures. The inferences are supported with simulated ice particle scattering calculations. A radar scattering model is used to explain the anomalous radial streaks in SHV $Z_{dr}$ and LDR.

1. Introduction

Many weather radars now achieve dual-polarization by transmitting both horizontal (H) and vertical (V) polarized waves simultaneously [simultaneous H and V (SHV) mode; also referred to as simultaneous transmit and receive (STAR) mode]. It is well known that cross coupling of the H and V waves occurs when the transmitted wave propagates through ice crystals that are aligned and have some mean canting angle significantly away from horizontal (Ryzhkov and Znić 2007; Wang and Chandrasekar 2006; Hubbert et al. 2010a,b). For example, electric fields are known to align ice crystals (Hendry et al. 1982; Caylor and Chandrasekar 1996; Metcalf 1995; Krehbiel et al. 1996) and cause negative $K_{dp}$ (specific differential phase). Such aligned canted ice particles can bias not only $Z_{dr}^{H V}$ (SHV $Z_{dr}$), but also linear depolarization ratio (LDR) in fast-alternating transmission of H and V polarizations operations [fast-alternating H and V (FHV) mode]. Biases in both $Z_{dr}^{H V}$ and LDR are readily evident as radial stripes in range. S-band polarimetric radar (S-Pol) SHV and FHV data gathered during the Terrain-Influenced Monsoon Rainfall Experiment (TiMREX) in close time proximity (with each other) are analyzed and used to infer the nature of the ice crystals that are responsible for the cross coupling and resulting observed polarimetric signatures.

Corresponding author address: J. C. Hubbert, National Center for Atmospheric Research, 3450 Mitchell Lane, Boulder, CO 80301.
E-mail: hubbert@ucar.edu

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Negative $K_{dp}$ in the ice phase in smaller convective cells, which is fairly common in the TiMREX S-Pol data, are shown and discussed in the context of storm electrification. High magnitudes of $K_{dp}$ (from both positive and negative $K_{dp}$) in the ice phase coupled with near-zero values of $Z_{\text{dr}}$ (FHV $Z_{\text{dr}}$) are explained and modeled as a population of two types of ice particles in the radar resolution volume: 1) aligned ice crystals that yield a high $|K_{dp}|$ and 2) randomly oriented (polarimetrically isotropic) larger ice aggregates or graupel that mask the high intrinsic $Z_{\text{dr}}$ of the aligned ice crystals. This was also modeled by Kennedy and Rutledge (2011) who used the T-matrix method to simulate the backscatter cross sections of populations of ice particles in winter storms. Here, the T-matrix method is also used but then the radar scattering model of Hubbert and Bringi (2003) is used to predict the bias in $Z_{\text{dr}}$ and LDR caused by cross coupling. Dual-Doppler synthesis data are presented along with sounding data, which support the microphysical interpretations.

This paper is organized as follows. Section 2 gives an overview of the TiMREX datasets including dual-Doppler synthesis, sounding and lightning data. Section 3 contains a discussion of ice crystal alignment in electrified convective storms. Section 4 describes the S-Pol SHV and FHV polarimetric signatures. Section 5 presents T-matrix simulations of ice particles that could cause the S-Pol polarimetric signatures. In section 6 the radar scattering model of Hubbert et al. (2010a) is used to explain the observed cross-coupling biases. A discussion of the observed storm is given in section 7. Conclusions follow in section 8.

## 2. The TiMREX dataset and storm overview

On 2 June 2008 both SHV and FHV datasets were gathered in close time proximity during TiMREX. On this day, a north–south line of convective cells formed to the south of S-Pol with trailing stratiform rain to the west. The storm cells were moving west to east. This dataset was also discussed in Hubbert et al. (2010b). In the following expanded analysis, $K_{dp}$, LDR, dual-Doppler synthesis and sounding data are added.

### Wind vector analysis, sounding and lightning data

The three-dimensional wind fields were retrieved via the variational multiple-Doppler radar wind synthesis method from Liou and Chang (2009). The conventional dual-Doppler synthesis method derives the vertical motion via upward–downward integration of the continuity equation with specified bottom–top boundary conditions. In contrast, the variational method derives the vertical motion via dynamical constraints and numerical smoothing terms including the anelastic continuity equation, the vertical vorticity equation, background wind, and spatial smoothness terms. The advantage of including the vertical vorticity equation is that there is no need to artificially prescribe the top or bottom boundary conditions for the vertical velocities in the traditional sense. Mewes and Shapiro (2002) have shown that the vertical vorticity equation helps determine the appropriate boundary conditions, which improves the recovery of the vertical velocities.

Four volume scans from two radars are used to construct the three-dimensional wind fields. Two volume scans from S-Pol were collected at 0616:19 and 0624:30 UTC and the other two volumes were collected by the operational Doppler Ken-Ting radar (RCKT), operated by Central Weather Bureau (CWB) of Taiwan, at 0616:56 and 0624:26 UTC. The radar datasets were processed to remove nonmeteorological echo and dealias the radial velocities, after which they were interpolated to Cartesian coordinates. The lower–upper-level displacement due to the radar volume time of about 7 min and the system advection (the system motion was about 7.7 and 9.4 m s$^{-1}$ in the $x$ and $y$ directions, respectively) were corrected as well. The synthesis domain was determined by considering the location of convective cells and the data coverage due to the scanning strategy and topography of southern Taiwan. The horizontal and vertical resolutions of the retrieved wind fields are 1.0 and 0.5 km, respectively, and the upper boundary is 15.0 km to include the echo top.

Figures 1 and 2 show storm-relative retrieved wind vectors from dual-Doppler wind analysis. Figures 1a–c show wind vectors overlaid on S-Pol reflectivity at 2.5, 5, and 7.5 km AGL, respectively. Figures 2a and 2b show wind vectors overlaid on S-Pol reflectivity along east–west vertical cross sections at 49 and 59 km south of S-Pol through two small convective cells of interest. The convective cells show moderate updrafts of 2–6 m s$^{-1}$ between 5 and 20 km in range in Fig. 2. Overlaid on the reflectivity plots of Fig. 1 are data from the lightning detection network of Taiwan, where the red $\times$ symbols indicate recorded in-cloud lightning discharges; there were no cloud-to-ground strikes recorded. Thus, there was electrification taking place in the general storm complex. Peak reflectivity values of about 36 dBZ were observed at the $-10^\circ$C level of these cells. The existence of 40 dBZ at the $-10^\circ$C is a usual rule of thumb for the onset of lightning (Zipser and Lutz 1994).

Figure 3 shows a skew $T$ plot from a sounding taken at 0600 UTC 2 June at about 80 km southwest along the 148° radial of S-Pol, that is, very close to the S-Pol radar data of Figs. 1 and 2. The black and blue solid lines indicate the temperature and dewpoint temperature ($^\circ$C), respectively, and the red dashed line is the estimated
FIG. 1. Storm-relative dual-Doppler wind vectors overlaid onto reflectivity at (a) 2.5, (b) 5, and (c) 7.5 km AGL. Positive (negative) vertical velocities (m s$^{-1}$) are in solid black (dashed white) contours. Small red times signs denote where electrical discharges were recorded by the Taiwan lightning detection network.
temperature (°C) of a convective parcel. The sounding is typical of tropical environments with a temperature lapse rate that is nearly moist adiabatic and deep moisture that extends to about 9-km altitude. The estimated convective available potential energy (CAPE) is over 1400 J spread from sea level to about 14-km altitude. The estimated parcel temperature is never more than 3° or 4° warmer than the environment. Thus this sounding supports deep convection with moderate updrafts and is consistent with the dual-Doppler observations of the presence of convective cells that reach up to almost 14 km and have maximum updraft speeds less than 10 m s⁻¹. The sounding shows temperatures of 0°C at 4.7 km, −6.7°C at 6.2 km, −20°C at 8 km, and −38°C at 10 km AGL with many levels at or near saturation. From Figs. 1–3 we conclude that the air is very likely saturated within the significant updrafts and that the environment is conducive to ice crystal growth by both deposition and riming. If both crystals and graupel are present, it is likely that charge separation is occurring also (Zipser and Lutz 1994), leading to the presence of electric fields. The polarimetric signatures of this region and associated simulations shown below are consistent with the electrification hypothesis.

3. Aligned ice crystals and storm electrification

There is some question as to what physical forces could align ice crystals that would then produce the observed polarimetric signatures to be discussed below. Here we argue that ice crystals by and large fall with their major (i.e., longer) axis horizontal and that storm electrification is required to vertically align ice crystals so that negative $K_{dp}$ is observed. Turbulence, even in

**Fig. 2.** Storm-relative dual-Doppler wind vectors overlaid on east–west vertical cross sections of reflectivity at $X = (a) −49$ and (b) −59 km. Positive (negative) vertical velocities (m s⁻¹) are in solid black (dashed white) contours. The horizontal red lines mark the 0°C level as determined by the sounding data given in Fig. 3. Dashed horizontal lines in Fig. 1 show the location of the vertical cross sections.
cumulonimbus clouds, has very little effect on ice crystal alignment.

The orientation of falling ice crystals has been well studied (Ono 1969; Sassen 1980; Cho et al. 1981; Klett 1995; Foster and Hallett 2002). For free-falling ice crystals in stagnant air in a nonelectrified environment, the crystals fall with their major axis horizontal. The stability of particles is dependent on the turbulence from shedding vortices created as the particles fall; the larger the fall velocity the greater the turbulence created. This is quantified via the Reynolds number. For plates, studies have shown that they fall with their long axis horizontal with little oscillation (Jayaweera and Mason 1965; List and Schemenauer 1971; Zikmunda and Vali 1972). For columnar ice crystals, if the axis ratio is less than 3, the crystals likewise fall with their long axis horizontal; if the axis ratio is greater than 3, rotations can occur but still a majority of the crystals remain horizontally oriented (Zikmunda and Vali 1972). Very small plate crystals (<30 μm) are subject to Brownian motion. Ice crystals with major axes of 1 mm with fall velocities of about 80 cm s$^{-1}$ have a Reynolds number (Re) of about 100. Ice crystals with Re $< 100$ fall with little deviation of their major axis from the horizontal (Sassen 1980; Foster and Hallett 2002).

Cho et al. (1981) considered the orientation of ice crystals in cumulonimbus clouds. They drew on experimental turbulence data (e.g., Rhyne and Steiner 1964) and then extrapolated that to the orientation scale of the ice crystals using the Kolmogorov $\nu_3$ law. Cho et al. (1981) show that this orientation scale is about 1 cm for the ice crystals considered, that is, 50 μm to 1 mm. They point out that $\nu_3$ law applies to the inertial subrange of eddies, and for the scale of interest here (1 cm), molecular viscosity becomes an important damping factor so that $\nu$, the energy density spectrum of eddies, decreases more quickly than that predicted by the $\nu_3$ law. Cho et al. (1981) conclude that turbulence has little effect on ice crystal orientation, that is, ice crystals will continue to fall with their major axes horizontal.

When uncharged ice particles are subjected to an electric field, charge is induced across the crystal, which...
creates an electric torque so that the ice particle is rotated from its original position (Weinheimer and Few 1987; Foster and Hallett 2002). Weinheimer and Few (1987) present calculations that indicate that electric fields of 100 kV m\(^{-1}\) can overcome aerodynamic forces to align ice particles 0.2–1 mm in diameter (major axis of the crystal). For ice crystals smaller than 50 μm, only about 50 kV m\(^{-1}\) or less is required (Saunders and Rimmer 1999; Foster and Hallett 2002) for orientation along electric field lines. There are also many polarimetric radar observations that show ice crystal orientation (Hendry and McCormick 1976; Hendry et al. 1982; Krehbiel et al. 1996; Caylor and Chandrasekar 1996; Metcalf 1997; Galloway et al. 1997; Scott et al. 2001; Ryzhkov and Zrnč 2007). The premise is that the observed negative \(K_{dp}\) in the ice phase is caused by ice crystals being aligned vertically by the electric field. After observed lightning discharges the negative \(K_{dp}\) signatures disappear (Caylor and Chandrasekar 1996; Metcalf 1997) as the electric field diminishes. Once the electrical forces are gone, the ice crystals will attain their natural aerodynamic orientation after times on the order of 10 ms (Cho et al. 1981).

4. S-Pol polarimetric signatures from TiMREX

In this section, the SHV and FHV polarimetric signatures from data gathered during TiMREX on 2 June 2008 corresponding to Figs. 1 and 2 are compared and analyzed, and a microphysical interpretation is given. Both datasets demonstrate the effects of cross coupling during propagation due to aligned, canted ice particles. Figure 4 shows FHV \(Z\), \(Z_{dr}\), and \(\phi_{dp}\) in the left-hand column while SHV \(Z\), \(Z_{dr}\), and \(\phi_{dp}\) are given in the right column. The FHV data were gathered at 0619:36 UTC while the SHV data were gathered at 0613:59 UTC, both at 8.6° elevation angle. Figure 5 shows the accompanying \(K_{dp}^{hv}\), \(K_{dp}^{shv}\), LDR\(_b\) (linear depolarization ratio for H transmit, hereinafter often just LDR) and \(\rho_{hv}\). The quantities LDR, \(Z_{dr}\), and \(\rho_{hv}\) clearly show the melting level at the 30-km range ring. The \(\rho_{hv}\) is not shown since it is very similar to \(\rho_{hv}^{shv}\).

Bias due to cross coupling is evidenced by the radial stripes beyond the melting level in \(Z_{dr}^{shv}\) of Fig. 4e and in LDR of Fig. 5b (Ryzhkov and Zrnč 2007; Hubbert et al. 2010b). These radial stripes are caused by aligned ice particles that have a nonzero mean canting angle. The most prominent stripes in \(Z_{dr}^{shv}\) and LDR are delineated by three dashed lines: lines (x), (y), and (z) mark the FHV data plots, while lines (u), (v), and (w) mark the SHV data plots. The lines do not mark the same region in the SHV and FHV data because of storm movement between the two measurement times. The middle lines mark approximately the radial where \(Z_{dr}^{shv}\) (LDR) decrease (increase) maximally. These two striped regions are the focus of our analysis. Similar X-band data are also shown in Hubbert et al. (2014).

Dashed line (w) for \(Z_{dr}^{shv}\) of Fig. 4e marks the approximate right edge of the decreasing, biased \(Z_{dr}^{shv}\) area. This decreasing \(Z_{dr}^{shv}\) region begins at about 45 km and extends to roughly 65 km in range, which corresponds to heights of 6.85 and 9.97 km AGL, and −10°C to −35°C, respectively. The two convective cells are seen in Fig. 4d marked by the higher reflectivities of about 35 dBZ along dashed line (w) at 50- and 60-km range. These two cells are also seen in the two vertical wind vector vertical cross sections of Fig. 2. Beyond 65 km, \(Z_{dr}^{shv}\) remains relatively constant along the radials between lines (u) and (w). The \(K_{dp}^{shv}\) of Fig. 5 shows two small areas with negative values (minimum of −0.8° km\(^{-1}\)) with the larger area located along dashed line (w) also at roughly 60-km range. The two negative \(K_{dp}^{shv}\) areas roughly correspond to the two higher reflectivity areas. We infer that a local electric field was produced by the convection in these areas, which vertically aligned the smaller ice particles, thus causing the negative \(K_{dp}^{shv}\). We also infer that since decreasing \(Z_{dr}^{shv}\) mostly occurs between 45 and 65 km, this is the region, between lines (w) and (u), where there are evidently aligned canted ice crystals causing the negative bias in \(Z_{dr}^{shv}\).

Next examine LDR in Fig. 5b. Dashed lines (x), (y), and (z) mark the region where LDR increases from −27 to about −12 dB. The region is analogous to the above decreasing \(Z_{dr}^{shv}\) region: both are caused by cross coupling due to aligned canted ice crystals and the intrinsic LDR of the canted ice crystals is masked by the LDR of the larger ice particles. For example, ice columns (plates) with an axis ratio of 3 (0.33) canted at 45° have an LDR of about −13 (−12) dB. It is difficult to say what the LDR is for the larger ice particles since the decreasing \(Z_{dr}^{shv}\) in this region than \(Z_{dr}^{shv}\) (Wang and Chandrasekar 2006). The region of the majority of the LDR increase is again roughly 45–65 km. Thus, this area from 45 to 65 km between lines (x) and (y) is analogous to the region in the SHV data from 40 to 65 km between lines (u) and (w). The \(Z_{dr}^{shv}\) of Fig. 4a shows the two convective cores along the line (z) again at about 50 and 60 km with peak reflectivities of about 33 dBZ. The two cores have advected to the east about 6 km during the 5.5-min time difference between the FHV and SHV scans. The \(Z_{dr}^{shv}\) can be considered to be a much more accurate estimate of the intrinsic \(Z_{dr}\) in this region than \(Z_{dr}^{shv}\) is since the effects of cross coupling are negligible on \(Z_{dr}^{shv}\) (Wang and Chandrasekar 2006). In the region of increasing LDR between lines (y) and (z), \(Z_{dr}^{shv}\) is slightly positive.
FIG. 4. S-Pol data from TiMREX: the (left) FHV and (right) SHV data are separated by 5.5 min.
on average. To the west between lines (x) and (y), $Z_{\text{dr}}^{\text{fhv}}$ is a bit more positive, especially along line (x) where $Z_{\text{dr}}^{\text{fhv}}$ is around 0.4 dB. In the next 15 km farther west beyond line (x) in the ice phase, $Z_{\text{dr}}^{\text{fhv}}$ is between 0.4 and 1 dB, and $K_{dp}$ is 0.3–0.8\(^{\circ}\) km\(^{-1}\) most everywhere.

Corresponding to the higher reflectivities along lines (z) and (w) are areas of negative $K_{dp}$ marked in green color scale in both the SHV and the FHV data of Figs. 5a and 5c. The peak negative $K_{dp}$ is approximately $-0.8^{\circ}$ km\(^{-1}\) for both the SHV and FHV data. This is a relatively large value in the ice phase and indicates that there is a significant population of ice particles with their major axis oriented near vertical and with large major to minor axis ratios. Examining the $Z_{\text{dr}}^{\text{fhv}}$, it is seen that the intrinsic $Z_{\text{dr}}$ in these regions is close to 0 dB. Simulations discussed below show that ice crystals that produce a $K_{dp}$ of $-0.8^{\circ}$ km\(^{-1}\) would also produce significantly negative $Z_{\text{dr}}$, smaller than $-3$ dB. Thus, in these regions there are likely two ice crystal population types: 1) a high concentration of near vertically aligned small ice crystals with a high axis ratio, resulting in negative $K_{dp}$, and 2) larger ice particles that are randomly oriented and dominate the backscatter signature, thus producing a near-zero $Z_{\text{dr}}$. Kennedy and Rutledge (2011) have modeled oriented dendrites in winter storms over the Front Range of Colorado with larger aggregates that masked the higher $Z_{\text{dr}}$ of the dendrites. Recently, Andric et al. (2013) also compiled scattering calculations for vertical profiles of polarimetric radar data using different types of ice particles for a winter storm in Oklahoma. Their model, however, was unable to predict their higher observed $K_{dp}$. The radar data and dual-Doppler analysis above indicate that weak convection was taking place (vertical velocities of 2–6 m s\(^{-1}\)) so that
ice crystals (columns and plates) were being produced (Bailey and Hallett 2009). It is very likely that electrification was occurring that aligned the ice crystals.

Moving west of lines (z) and (w), the amount of cross coupling increases, as is evidenced in the $Z_{\text{fv}}$ and LDR plots (Figs. 4e, 5b), until lines (y) and (u), which mark the radials of near maximum cross coupling. Lines (y) and (u) also approximately mark the transition area between the negative $K_{\text{dp}}$ and positive $K_{\text{dp}}$ areas. Moving farther to the west to lines (x) and (v), the amount of cross coupling decreases while $K_{\text{dp}}$ increases. These lines also mark the radials of maximum $\phi_{\text{dp}}$ accumulation as seen Figs. 4c,f. Reflectivities also decrease to 15–20 dBZ. The $K_{\text{dp}}$ is high with a maximum of 1° km$^{-1}$; however, $Z_{\text{fv}}$ is only slightly positive around 0.5 dB on average. Again, this indicates that there are two ice crystal population types: 1) smaller, near horizontally aligned ice crystals that give high $K_{\text{dp}}$ and 2) larger randomly oriented particles that mask the high $Z_{\text{dr}}$ of the horizontally aligned crystals.

Summarizing, the polarimetric signatures indicate that along lines (z) and (w) there are vertically aligned ice crystals mixed with larger aggregates or graupel. The vertical alignment is very likely due to the presence of electric fields. Moving to the west, the electric field gives ice particles a mean canting angle of around 45° (projected onto the radar plane of polarization) along lines (y) and (u) where cross coupling is maximized (Hubbert et al. 2014). Moving farther west where there are apparent weak electric fields so that vertical alignment does not occur, the ice crystals are horizontally aligned likely by aerodynamic forcing along lines (x) and (v) where $K_{\text{dp}}$ becomes quite positive, maximum $\phi_{\text{dp}}$ accumulation occurs and the cross coupling is greatly reduced. Moving even farther west, additional radial streaks in $Z_{\text{dr}}$ and in LDR are seen, indicating that the ice crystals obtain mean canting angles significantly away from 0° so that cross coupling again occurs. However, the mean canting angle does not exceed ±45° since $K_{\text{dp}}$ remains positive (Hubbert et al. 2014; Ryzhkov and Zrnić 2007). The observed negative $K_{\text{dp}}$ at the far southern edge of the storm are due to low signal-to-noise ratio (SNR) and are artifacts of the $K_{\text{dp}}$ algorithm rather than microphysics. The $Z_{\text{fv}}$ remains around 0 dB or slightly positive through the western region where $K_{\text{dp}}$ is quite positive (0.3 to 0.8° km$^{-1}$) again indicating the coexistence of two populations of ice particle types as discussed above.

To illustrate the vertical structure of the negative $K_{\text{dp}}$ and the accompanying radar signatures, Fig. 6 shows a radial vertical cross section of FHV $Z$, $Z_{\text{dr}}$, $K_{\text{dp}}$ and $\rho_{\text{hv}}$, as labeled, along line (z) of Fig. 5a. In the area of negative $K_{\text{dp}}$, $Z_{\text{dr}}^{\text{fv}}$ is −0.1 to −0.3 dBZ, $Z_{\text{dr}}^{\text{hv}}$ is 25 to 35 dBZ, and $\rho_{\text{hv}}^{\text{fv}}$ is quite high indicating good data quality. Negative $K_{\text{dp}}$ such as seen in Figs. 5a and 5c are fairly common in TiMREX data. Figure 7 show three more examples of negative $K_{\text{dp}}$. All of these three cases are associated with shallow convective cores (there are several more cases not shown here). The reflectivities are in the 23–35-dBZ range, $Z_{\text{dr}}$ is close to 0 dB, $\rho_{\text{hv}}$ is high (>0.98), and, typically, radial LDR streaks are associated, indicating that canted ice particles are causing cross coupling. Thus, electric fields are likely present in these regions.

5. T-matrix modeling of ice crystals

To corroborate the inferences about the types of ice particles that cause the observed polarimetric signatures, we next simulate ice particle backscatter cross sections.

a. Model description

The scattering model used is described in Waterman (1969) and Vivekanandan et al. (1993), which employs the T-matrix method to calculate the 2 × 2 scattering matrix, then integrates over the specified size and orientation distributions and creates the 4 × 4 Mueller matrix. The wavelength is 11 cm. The model was modified so that arbitrary mean canting angles for ensembles of particles could be included. This was accomplished by using the Fisher distribution (Fisher 1953; Mardia 1972), which is equivalent to a two-dimensional Gaussian distribution that has been mapped to a sphere. The functional form is

$$g_{\phi}(\theta, \phi) = c \exp\{\kappa[\cos\theta \cos\phi + \sin\theta \sin\phi (\cos(\phi - \delta)))]\sin\theta, \quad 0 < \theta < \pi, \quad 0 < \phi < 2\pi, \quad \kappa > 0,$$

where $\theta$ and $\phi$ are the latitude and longitude angles of a spherical coordinate system, $\delta$, $\delta$ specify the mean canting direction, $\kappa$ controls the spread of the distribution, and

$$c = \frac{\kappa}{4\pi \sinh \kappa}.$$

For details of the Fisher distribution, see Mardia (1972) and Hubbert and Brini (1996).

The T-matrix simulations model ice crystals as prolate spheroids (e.g., columns) or as oblate spheroids (e.g., plates, dendrites). The axis ratio (AR) is defined as

$$\text{AR} = \frac{c\text{-axis length}}{a\text{-axis length}},$$

where the c axis is perpendicular to the ice crystal basal face and the a axis is perpendicular to the c axis. Thus,
columns have axis ratios greater than 1 while plates have axis ratios less than 1.

There are no in situ measurements of ice particles for this storm. Rather than using a theoretically constructed particle size distribution (PSD), we use a measured PSD gathered on 10 June 2001 in Florida as part of the Airborne Field Mill (ABFM) project, at 2218:50 UTC at $219.5^\circ$C where the electric field was $E_z (kV m^{-1}) = -36.14$. The idea is to examine particle distributions that occur in similar typical environmental conditions as in Taiwan convective storms with electric fields present. Figure 8 shows a PSD and particle images collected by the high-volume precipitation spectrometer (HVPS; wider right-hand-side image field) and the two-dimensional cloud particle imaging (2D-C) probe (narrower left-hand-side image field). The blue and red lines are the PSD deduced from the 2D-C and HVPS probes, respectively. Together they yield a total PSD. It is well known that the 2D-C probes can overestimate the number of smaller particles because of shattering. For the PSD used here, software-based shattering corrections from Field et al. (2006) were used to minimize the shattering artifacts based on particle interarrival times.

Examining Figs. 4a and 4d there are two higher reflectivity areas that mark the top of small convective cores at roughly 50 and 60 km along the dashed line ($z$) for FHV data and along dashed line ($w$) for SHV data. The dual-Doppler analysis and sounding data discussed earlier indicated that convection was present and that the rising air parcels are very likely saturated. These conditions are favorable for both ice crystal growth by vapor deposition (Bailey and Hallett 2009) as well as larger particle growth by riming. Simulations below show that high-density, high-axis-ratio ice crystals (e.g., columns, needles, and plates) are likely present. Charge separation is likely occurring in the convective regions, creating electric fields that in turn align ice crystals.

### b. Ice particle scattering calculations

In this section we show scattering calculations for prolate and oblate spheroids for an experimentally gathered PSD for various particle densities. The idea is not to ascribe the observed polarimetric signatures to exact ice particle types. Rather we show a series of simulations that allow us to describe the bulk character of ice particles that would cause the observed polarimetric signatures.
Fig. 7. Three examples of negative $K_{dp}$ with accompanying $Z_H$, LDR, $Z_{dr}$, and $\rho_{hv}$. 
The PSD of Fig. 8 is partitioned into two regimes: 1) smaller aligned ice columns or plates that will yield significant $K_{dp}$, and 2) larger randomly oriented ice aggregates or graupel (with near-0 dB $Z_{dr}$), which will mask the high $Z_{dr}$ signatures of the aligned ice crystals. This dichotomy is not completely arbitrary. The calculations of Weinheimer and Few (1987) show that electric field strengths in excess of 100 kV m$^{-1}$ are required to align ice crystals with major dimension greater than 1 mm, whereas smaller ice crystals can be aligned by fields less than 100 kV m$^{-1}$. Since there was no lightning detected in the convective cells of interest, we assume that smaller electric field strengths were present so that larger ice particles might not be aligned. Scattering simulations for the smaller ice crystals are given in Table 1 for ice columns and in Table 2 for plates for various densities, axis ratios and maximum dimension. Both the columns and plates are given a Fisher orientation distribution with their longer axes horizontal (mean) in the plane of polarization and with a distribution of angles defined by $\kappa = 600$, which is equivalent to a standard deviation of 3.5$^\circ$ (Hubbert and Bringi 1996). The maximum major axis dimension is either 0.587 or 0.95 mm. The axis ratios used are in agreement with experimental observation (Ono 1969). Since the ice crystals are relatively small, the density is first taken as 0.917 g cm$^{-3}$, that is, solid ice. This density then yields an upper bound for $K_{dp}$ and $Z_{dr}$ for the assumed PSD. Rasmussen et al. (1999) list bulk densities for different types of plates and dendrites with almost all categories having densities greater than 0.5 g cm$^{-3}$ (an exception is stellar dendrites with a density of 0.44 g cm$^{-3}$). Thus our simulations are repeated for a density of 0.5 g cm$^{-3}$ and the results are given in Tables 1 and 2. From these tables several observations can be made about the bulk nature of the ice crystals. For a density of 0.5 g cm$^{-3}$, the $K_{dp}$ values are less than the experimentally observed 0.8$^\circ$ km$^{-1}$. However, $K_{dp}$ could be increased by increasing the number density of the ice particles; otherwise, it is likely that the ice particles have densities greater than 0.5 g cm$^{-3}$. It can be inferred that for ice crystals less than 1 mm for the PSD considered here, the density needs to be greater than 0.5 g cm$^{-3}$ to achieve the observed $K_{dp}$ of 0.8$^\circ$ km$^{-1}$. This would exclude stellar dendrites as a possible particle type, at least according to Rasmussen et al. (1999). If the density is close to solid ice, only particles with diameters of $\leq$0.587 mm need to be aligned to yield $K_{dp}$ of 0.8$^\circ$ km$^{-1}$ or greater. Thus, weaker electric fields are sufficient to align these smaller ice particles. There are very likely ice particles in this size category that are neither columns nor plates; however, in bulk the population must possess a significant axis ratio and density to produce the observed polarimetric signatures.

As part of the modeling we include the calculated ice water content (IWC) for the various PSDs in Tables 1 and 2. The IWC are obtained by integrating the assumed PSD, particle shapes, and bulk densities. While we are unsure as to the exact type of ice particles or their densities that exist in regions where the SHV $Z_{dr}$ radial streaks occur, our assumed densities and calculated...
IWC agree reasonably well with experimental observations (Heymsfield et al. 2004; Rasmussen et al. 1999).

The experimentally observed negative $K_{dp}$ indicates that there were aligned ice crystals with their longer axis near vertical. For plates with their major axis vertical, aerodynamic torque would not align the shorter axes (c axis) so that they would be free to rotate around their longer aligned axes and this would reduce the magnitude of both $K_{dp}$ and $Z_{dr}$. Foster and Hallett (2008) show that strong nonuniform electric fields can provide a secondary electric torque that could align the c axis of the vertically oriented plates. However, it is not necessary that the c axis be aligned to obtain negative $K_{dp}$. This is demonstrated next with simulations. The a axis (longer axis) of the plates modeled in Table 2 are given a Gaussian distribution so that the mean canting angle is vertical with a standard deviation of $3.5^\circ$. The c axis is given a uniform random orientation distribution. The results are given in Table 3 for a density of 0.917 g cm$^{-3}$. The magnitude of $K_{dp}$ has been reduced by about a factor of 2 as compared to Table 2. Thus, vertically aligned high-density plates, with their secondary axis randomly oriented, can produce the experimentally observed negative $K_{dp}$. Obviously, from Table 1, vertically

<table>
<thead>
<tr>
<th>$\rho_d$ (g cm$^{-3}$)</th>
<th>AR</th>
<th>$D_{max}$ (mm)</th>
<th>Z (dBZ)</th>
<th>$Z_{dr}$ (dB)</th>
<th>$K_{dp}$ (° km$^{-1}$)</th>
<th>IWC (g m$^{-3}$)</th>
</tr>
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<tr>
<td>0.917 2 0.587 15.9 2.78 0.57 0.205</td>
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<tr>
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<tr>
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<tr>
<td>0.5 3 0.587 10.7 2.21 0.26 0.050</td>
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<td></td>
</tr>
<tr>
<td>0.5 4 0.587 11.0 2.58 0.31 0.028</td>
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</tr>
<tr>
<td>0.5 5 0.587 11.2 2.79 0.33 0.018</td>
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<tr>
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<tr>
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</tbody>
</table>

Table 2. As in Table 1, but for ice plates.
aligned ice columns can give the required negative $K_{dp}$ also.

6. Modeling propagation effects

The radar scattering model of Hubbert et al. (2010a) is now used to demonstrate the observed cross-coupling signatures in $Z_{dr}^{hv}$ and LDR. Here we arbitrarily choose ice columns with a maximum size of 0.95 mm, an axis ratio of 3, and a density of 0.7 g cm$^{-3}$. The T-matrix simulations are $Z = 21.2$ dBZ, $Z_{dr} = 3.20$ dB, $K_{dp} = 0.84$ km$^{-1}$, and IWC = 0.115 g m$^{-3}$, with the $K_{dp}$ matching well the experimentally observed $K_{dp}$. Matrosov et al. (2005) used $K_{dp}$-band data to estimate the angular flutter of pristine dendritic ice crystals to be about 10$^\circ$. If in our scattering calculations in Tables 1 and 2 the standard deviation of canting angles is increased from 3.5$^\circ$ to 10$^\circ$, the resulting $Z_{dr}$ and $K_{dp}$ values change by less than 4$\%$ (including the present case). The level $Z_{dr} = 3.20$ dB is much higher than the experimentally observed 0 to 1 dB $Z_{dr}^{hv}$ in Fig. 4b, which is considered indicative of the intrinsic $Z_{dr}$. The remaining larger particles (>0.95 mm) from the PSD of Fig. 8 are now modeled as graupel with a 0.9 axis ratio and a uniform random orientation distribution. The bulk density is 0.3 g cm$^{-3}$. The T-matrix simulation results for the graupel are $Z = 35.7$ dBZ, $Z_{dr} = 0$ dB, $K_{dp} = 0$, and IWC = 1.234 g m$^{-3}$. The total IWC then is 1.35 g m$^{-3}$, which is high but is reasonable for a reflectivity of 35 dBZ. The ice columns are now given a mean canting angle that is vertical and then combined with the graupel. The simulation gives $Z = 35.9$ dBZ, $Z_{dr} = -0.1$ dB, and $K_{dp} = -0.84$ km$^{-1}$. If the density of the graupel is reduced to 0.2 g cm$^{-3}$, then $Z = 32.5$ dBZ, $Z_{dr} = -0.17$ dB, $K_{dp} = -0.84$ km$^{-1}$, and IWC = 0.822 g m$^{-3}$. This simulation shows how it is possible to achieve relatively high reflectivities, negative $K_{dp}$, and small negative $Z_{dr}^{hv}$, as shown in Fig. 6.

Table 3. Modeled data for vertically oriented ice plates. The density is 0.917 g cm$^{-3}$ (i.e., solid ice). The plates’ longer axes are oriented vertically with a standard deviation of 3.5$^\circ$. The c axes are distributed uniformly random in the horizontal plane.

<table>
<thead>
<tr>
<th>AR</th>
<th>$D_{max}$ (mm)</th>
<th>$Z$ (dBZ)</th>
<th>$Z_{dr}$ (dB)</th>
<th>$K_{dp}$ (° km$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.587</td>
<td>14.7</td>
<td>−2.68</td>
<td>−0.74</td>
</tr>
<tr>
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<td>0.587</td>
<td>14.2</td>
<td>−2.31</td>
<td>−0.58</td>
</tr>
<tr>
<td>0.3</td>
<td>0.587</td>
<td>14.0</td>
<td>−1.96</td>
<td>−0.46</td>
</tr>
<tr>
<td>0.1</td>
<td>0.95</td>
<td>21.6</td>
<td>−2.68</td>
<td>−1.15</td>
</tr>
<tr>
<td>0.2</td>
<td>0.95</td>
<td>21.1</td>
<td>−2.31</td>
<td>−0.90</td>
</tr>
<tr>
<td>0.3</td>
<td>0.95</td>
<td>20.8</td>
<td>−1.96</td>
<td>−0.71</td>
</tr>
</tbody>
</table>

to obtain reflectivities greater than 30 dBZ, negative $K_{dp}$, and near-0 dB $Z_{dr}$ requires some combination of small vertically aligned crystals combined with larger, nearly spherical particles. It is interesting to note that it is possible to simulate columnar ice with observed PSDs that are small enough to be vertically aligned by relatively weak electric fields and result in the observed polarimetric signatures. This lends confidence that the scenario described above is plausible in nature even though we do not have direct observations of it.

To model the bias caused by propagation effects, we now give the ice columns a mean canting angle of 45$^\circ$ and let the density of the graupel be 0.2 g cm$^{-3}$. This density is perhaps low for graupel but this is done to better match the observed reflectivity along lines ($y$) and ($v$) in Fig. 4. The PSD will be variable across the region of interest but we choose to continue to use the PSD of Fig. 8 for continuity. A mean canting angle of 45$^\circ$ will minimize $K_{dp}$ while maximizing the cross coupling and the corresponding bias in SHV $Z_{dr}$ and LDR (Hubbert et al. 2014). The modeled results are $Z = 32.4$ dBZ, $Z_{dr} = 0$ dB, $K_{dp} = 0$ km$^{-1}$, and LDR = −27.5 dB. The covariance matrix for the ensemble (not given here) then describes FHV data for the backscatter volume and does not account for propagation effects. To include propagation effects, and to simulate SHV data, the model presented in Hubbert et al. (2010a) is used. The propagation medium is given a mean canting angle of 45$^\circ$ and the covariance matrix generated from the model above for ice columns canted at 45$^\circ$ mixed with graupel is used to model the backscatter medium. Note that the larger randomly oriented ice particles, which are polarimetrically isotropic, do not affect the propagation matrix. Figure 9 shows $Z_{dr}^{hv}$ (solid curve) and LDR$_{h}$ (dashed curve) that result from the model, plotted as a function of principal plane $\phi_{dp}$ ($\phi_{dp}^p$). (The quantity $\phi_{dp}^p$ is the intrinsic $\phi_{dp}$ of the medium when the ice crystals possess a mean canting angle of 0.) If the ice crystals possess a non-zero mean canting angle, the $\phi_{dp}^p$ does not change (i.e., is independent of mean canting angle); however, the measured $\phi_{dp}$ in the H–V polarization bases will change. As can be seen, after 25$^\circ$ of principal plane $\phi_{dp}$, $Z_{dr}^{hv}$ decreases to −2.5 dB and LDR increases to −13 dB, which mimics the behavior seen along dashed lines ($y$) and ($v$) in Fig. 4e and Fig. 5b.

The quantity $Z_{dr}^{hv}$ is a strong function of the transmit differential phase $\arg(E_v^*E_h^*)$, where the two quantities in the parentheses are the transmitted V and H electric fields, respectively (Ryzhkov and Zrnić 2007; Hubbert et al. 2014). For Fig. 9, the transmit differential phase was chosen as −40$^\circ$ since this value gave model results
that match well the experimental data. The transmit differential phase of S-Pol is unknown. The $K_{dp}$ in Figs. 5a and 5b along dashed lines ($u$) and ($w$) between 45- and 60-km range is positive with a maximum of 0.85° km$^{-1}$. The reflectivities are 15–20 dBZ and $Z_{dr}^{shv}$ become more positive by a few tenths of a decibel as compared to the negative $K_{dp}$ regions along dashed line ($z$) and ($w$). Thus, the nature of the ice crystals has changed in this region; however, for continuity, the PSD of Fig. 8 is again used. To achieve these lower reflectivities with high $K_{dp}$, the aligned small crystals need a smaller maximum diameter ($D_{max}$). Thus, the $D_{max}$ is reduced to 0.437 mm. Again, since $Z_{dr}$ is relatively small, these smaller ice crystals exist with larger randomly oriented ice particles. Accordingly, plates are modeled with a density of 0.87 g cm$^{-3}$ with an axis ratio of 0.1. The results are $Z = 10.6$ dBZ, $Z_{dr} = 7.57$ dB, and $K_{dp} = 0.70°$ km$^{-1}$. The larger ice particles greater than 0.437 mm are given a density of 0.05 g cm$^{-3}$ (more indicative of aggregates). The results are $Z = 20.3$ dBZ, $Z_{dr} = 0$ dB, and $K_{dp} = 0°$ km$^{-1}$. Combining the aligned plates with the larger particles gives $Z = 20.7$ dBZ, $Z_{dr} = 0.37$ dB, and $K_{dp} = 0.71°$ km$^{-1}$. This then matches fairly well the observed average radar signatures along dashed lines ($u$) and ($v$).

**LDR and canted ice crystals**

From the discussion above and Fig. 5b, it is apparent that cross coupling affects LDR in a similar fashion to $Z_{dr}^{shv}$. Thus, for radars that use FHV transmit mode to achieve dual polarization, LDR can be used to detect canted ice crystals if there is sufficient sensitivity. Shown in Fig. 10 is LDR as a function of principal plane $\phi_{dp}$ with the mean canting angle of the propagation medium as a parameter. The background LDR is $-35.4$ dB in Fig. 10a and $-29.5$ dB in Fig. 10b. This background value is intended to model the LDR system limit (sensitivity) of the radar. This is the smallest LDR that is detectable by radar, which is usually limited by the isolation performance of the antenna. The $-35.4$ dB represents what an excellent center-fed parabolic antenna might be and $-29.5$ dB is approximately the LDR system limit of S-Pol. A radar with a lower LDR system limit is much more sensitive to canted ice particles as is seen in Fig. 10a. LDR will be a function of both the backscatter medium as well as the propagation cross coupling. Like $Z_{dr}^{shv}$, the LDR bias caused by cross coupling will remain along the remainder of that radial and it will appear as a radial streak. Unlike $Z_{dr}^{shv}$, LDR is not a function of the transmit differential phase.

7. Discussion

There were no electric field or particle probe measurements made during TIMREX. However, there is a unique combination of other measurements along with previous research studies that allows for reasonable inferences to be made about the particle types, alignment, and the electric fields.

The radar data and simulations show strong evidence for the coincident presence of both smaller ice crystals with large axis ratios together with aggregates, rimed aggregates, or graupel. In the absence of electric fields, aerodynamic forces cause the longer axis dimension of ice crystals to align horizontally. In regions outside of the convective updrafts and the $Z_{dr}^{shv}$ bias stripes, this is evidenced by small $Z_{dr}^{shv}$ ($<0.5$ dB) and strongly positive $K_{dp} (0.5°-0.8°$ km$^{-1})$. Here, since $Z_{dr}^{shv}$ is proportional to the reflectivity weighted mean axis ratio (Bringi and Chandrasekar 2001), it is dominated by the largest particles that appear spherical in bulk (i.e., randomly oriented, or polarimetrically isotropic), while $K_{dp}$ is sensitive to the smaller, horizontally aligned crystals, resulting in positive values. The $K_{dp}$ is insensitive to particles that appear spherical in bulk. In regions within the convective updraft the large axis ratio crystals are oriented with their long axis aligned vertically. The vertically aligned ice results in the negative $K_{dp}$ and the larger ice particles yield the near-0 dB intrinsic $Z_{dr}$. As discussed above, the most likely mechanism for aligning the crystals in the vertical is the presence of a vertical electric field. In fact, to our knowledge there are no
other known mechanisms that would vertically align anisotropic ice crystals over regions as large as the observed negative $K_{dp}$. It is natural to consider if an electric field was indeed present, as there were no lightning detections in the convective cells of interest. However, there were lightning discharges recorded by the Taiwan lightning detection network 25 km to the north of the convective cell located along the 249-km east–west cut shown in Fig. 1. Even if the storms did not produce lightning, it is very likely that charge separation occurred and electric fields were present but were below the threshold required to initiate lightning.

Given the presence of an updraft in the humid environment (Figs. 2, 3), it is very likely that supercooled liquid was present in the convective towers and thus riming was occurring. It has been suggested that a mixed-phase environment driven by an updraft results in noninductive charging through particle collisions in the presence of supercooled water (Workman and Reynolds 1949; Williams and Lhermitte 1983; Dye et al. 1988; Rutledge et al. 1992; Carey and Rutledge 1996; Petersen et al. 1996, 1999; Deierling et al. 2008). These collisions transfer charge between the large riming particles and the smaller ice crystals and the sign and magnitude of the charge exchanged depends upon quantities such as the temperature, liquid water content and contaminants, for example, various salts [MacGorman and Rust (1998) provide a good summary]. The charge separation is thought to occur because of the different fall speeds of the larger precipitating ice and the smaller ice crystals that are lofted by the updraft. The analyzed storms have modest but significant updrafts at temperatures from $0^\circ$ to $-40^\circ$C. Therefore, it is highly likely that the electric fields are present in the convective updrafts that display the negative $K_{dp}$ signatures in this study.

Takahasi (1983) measured electric fields in tropical convection using balloon borne instruments and found a maximum of about 90 kV m$^{-1}$ at an altitude around 8 km (MacGorman and Rust 1998). Unfortunately the minimum electric field strength required to produce lightning is not well defined (MacGorman and Rust 1998), so it is not possible to put any upper bounds on the field strength in our analysis. MacGorman and Rust (1998) describe in detail the electric field of several types of non-lightning-producing clouds. Recently Mach et al. (2009) and Mach et al. (2011) estimated storm conduction currents above lightning and non-lightning-producing clouds and grouped the results in land and oceanic regimes using measurements from 850 overflights of the National Aeronautics and Space Administration (NASA) ER-2 and Altus-II aircraft. They found significant currents above oceanic, non-lightning-producing clouds indicating significant electric fields. Interestingly, the measured conduction currents for both lightning and non-lightning-producing clouds over the ocean were stronger than their counterparts over land. Given the evidence in the literature that electric fields are present in non-lightning-producing clouds, in particular oceanic convection, it is reasonable to expect electric fields in the convective updrafts that display the negative $K_{dp}$ signatures in this study.

There were no in situ particle measurements to verify the mixture of particles present. However, the production of large, randomly oriented aggregates or graupel together with smaller oriented ice crystals with an electric field is not unexpected in convection in the
TiMREX environment. The large particles that are responsible for the high reflectivity and near 0-dB \(Z_{\text{dr}}\) measurements above the melting level could be frozen drops, graupel, rimed or dry aggregates, or some combination of these. Frozen drops could result from liquid drops that are carried above the 0°C level by the updraft and subsequently freeze. Graupel would result from riming of supercooled liquid onto frozen drops or aggregates.

Smaller, high-axis-ratio ice crystals could form from the activation of ice nuclei within the updraft or from one of various ice multiplication processes. Overviews of ice multiplication can be found in Houze (1993) and Pruppacher and Klett (1997). There is no way to know for certain the habit of ice crystals that are producing the observed \(K_{\text{dp}}\) signatures. The ice crystal habit that grows varies in a complex manner with temperature and water vapor content. The Nakaya diagram (Nakaya 1954; Kobayashi 1961; Pruppacher and Klett 1997) describes the crystal habits grown in a laboratory setting as a function of temperature and humidity. However, natural differences in the environment such as electric field and chemical contaminants can alter significantly the habit and growth rates of crystals (Libbrecht and Tanusheva 1999; Knight 2012). In the clouds in the current study, there are a few factors favoring needle or columnar crystal growth in the lower parts of the storm. Needle or column growth is seen in the Nakaya diagram and in temperatures between about \(-4^\circ\) and \(-9^\circ\)C. The electric field that is present in the clouds as evidenced by the signature of vertically aligned crystals could also act to accelerate the needle growth rate (Libbrecht and Tanusheva 1999). Also at these temperature ranges the rime splintering process (Hallett and Mossop 1974) may be actively producing additional needles. Since the updrafts in this region of the cloud are fairly modest (about 2–6 m s\(^{-1}\)), these needles and/or columns may spend significant time within the temperature range favorable for their growth. Libbrecht and Tanusheva (1999) also found that needle growth was extended to colder temperatures (\(-15^\circ\)C) with an electric field through suppression of branching. At colder cloud temperatures, the dominant habit regime would be plates and dendrites. Given these different growth regimes as well as processes such as aggregation and crystal fracturing it is likely that there is a variety of crystal types mixed together. However, since needles, columns, and plates have all been shown to produce the observed \(K_{\text{dp}}\) signatures, the likely mixture of crystal habits does not change the interpretation that there are a population of oriented crystals mixed with larger ice particles that are producing the observed radar signatures.

8. Summary and conclusions

In this paper, cross coupling of simultaneously transmitted H and V waves, due to canted ice crystals, was presented, simulated, and analyzed. Microphysical interpretations were offered. Both SHV and FHV S-Pol data from TiMREX were examined in detail. The analyzed SHV data and FHV data were gathered within 5.5 min of each other in a convective storm complex so that polarimetric signatures could be compared. Cross coupling in the ice phase was evident from radial steaks in \(Z_{\text{dr}}\) and LDR. Three regions surrounding the cross-coupling signatures were examined and micophysically interpreted: 1) an area with negative \(K_{\text{dp}}\), \(Z_{\text{dr}}\) of about 0 dB, and high reflectivity; 2) an area with small \(K_{\text{dp}}\), near-zero \(Z_{\text{dr}}\), maximum cross coupling, and somewhat smaller reflectivity; and 3) an area with high positive \(K_{\text{dp}}\), small positive \(Z_{\text{dr}}\) (about 0.5 dB on average), maximum \(\phi_{\text{dp}}\) accumulation, and small cross coupling. All three areas can be characterized by two distinct populations of ice particles: 1) smaller aligned ice crystals (columns or plates) with large major to minor axis ratios that cause large \(K_{\text{dp}}\) with relatively small reflectivity and 2) larger randomly oriented ice particles with larger reflectivity that mask the \(Z_{\text{dr}}\) of the smaller aligned ice crystals. Sounding data and dual-Doppler analysis showed that moderate updrafts of 2–6 m s\(^{-1}\) were present in a humid environment and likely resulted in supersaturated conditions (with respect to ice), supercooled liquid water, and rimed particles in the convective updrafts. Because of the observed negative \(K_{\text{dp}}\) (minima of \(-0.8^\circ\text{km}^{-1}\)), an electric field was likely present that aligned the columns or plates of high axis ratio and high density. Since the reflectivity was high in this region and \(Z_{\text{dr}}\) was close to 0 dB, larger graupel particles were likely present. The presence of ice crystals with graupel and supercooled liquid in an updraft are conditions conducive for charge separation. The negative \(K_{\text{dp}}\) was observed at other times and in other storms of similar composition and character: moderate storm depth with likely moderate updrafts, high reflectivities in ice, 6–10 km AGL, high \(p_{\text{hv}}\), and near-zero \(Z_{\text{dr}}\). Both LDR streaks and high \(K_{\text{dp}}\) areas are typically associated with the negative \(K_{\text{dp}}\) areas as was illustrated in three cases in Fig. 7. The ensuing electric field could further accelerate ice crystal growth and possible fragmentation so that there is an abundance of small crystals with high axis ratios that are able to cause the observed high \(K_{\text{dp}}\).

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