Examining the effect of the vertical wind shear environment on polarimetric signatures in numerically-simulated supercells

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Some Overarching Questions

• What relative hydrometeor types and concentrations comprise some of the commonly-observed polarimetric signatures?

• How are the polarimetric signatures related (spatially and temporally) to the kinematic and thermodynamic structure of supercells?

• What do changes in the polarimetric structure of a supercell reveal about the evolution of the kinematic and thermodynamic fields?
  • What is happening within the supercell when the ZDR column changes height/size? Are there situations in which the mid-level $\rho_{HV}$ ring is particularly evident/absent? Etc.

• How do polarimetric structures of simulated supercells vary in environments characterized by different shear profiles?

• How do polarimetric signatures vary by radar frequency (i.e., X, C, and S bands)? Where is this difference greatest, and which signatures are most affected?
Polarimetric Signatures In Supercells

Adapted from Kumjian and Ryzhkov (2007)

From Romine et al. (2008)

From Snyder et al. (2013)
Some X-Band Observations

From Snyder et al. (2013)
Why use numerical simulations?

- We have observational datasets of supercell from polarimetric mobile radars (e.g., UMass XPol and RaXPol), but practical limitations to deployment durations and strategies often complicates data collection (max height of data may not be great, attenuation is often very significant).

- Where data are available, one may be able to crudely estimate physical quantities such as temperature, rainwater mixing ratio, vertical velocity, etc.

- There are many caveats when applying idealized simulations to real-world data, but the goal is to extract meaningful signals and trends from the numerical simulations that can be used to infer processes behind observed polarimetric fields (from a nowcast/forecast perspective, etc.)
Model Configuration

- ARPS 5.3.3
- 150 km x 150 km x 20 km grid
- 200 m $\Delta X$ and $\Delta Y$, stretched vertical grid (75-350 m $\Delta Z$)
- Horizontally-homogeneous initial conditions
- 1.0 s $\Delta T$, run to 10800 s (output every 120 s)
- Radiation LBCs, Rayleigh damping layer at top, free-slip lower BC

Initial soundings:
- Weisman and Klemp (1982) thermodynamic profile
- A suite of vertical wind profiles
  - Four “shapes” at two “intensities” (hodograph lengths)
Microphysics and Radar Emulator

- Utilized Milbrandt and Yau (2005) triple-moment bulk scheme
  - Predicts N, Q, Z (i.e. M0, M3, M6)
  - Rain water, cloud water, ice, snow, graupel, and hail
  - Multimoment scheme is needed to model sedimentation and to more accurately capture other microphysical processes
- Radar emulator used the framework of Jung et al. (2010) with updates to fractional water and dielectric constant calculations
  - Scattering matrix calculated from T-matrix method
  - $Z_H$, $Z_{DR}$, $Z_{DP}$, $\rho_{hv}$, $K_{dp}$
- No plots shown will include attenuation
- Desire: use a spectral bin scheme to more accurately stimulate microphysical processes. Limited schemes are available, however, and they tend to come with a high computational cost
Scattering at S, C, and X bands

- Mean canting angle: 0°
- Std. deviation of canting angle:
  - Rain: 0°
  - Hail: \( \begin{cases} 60° (1 - 2f_w) & f_w \leq 0.5 \\ 0 & f_w > 0.5 \end{cases} \)
- Aspect ratio:
  - Rain: Brandes et al. (2002)
  - Hail: 
    \[
    \begin{cases}
    0.75 & f_w < 0.2 \\
    0.813 - 0.317f_w & 0.2 \leq f_w < 0.8 \\
    2.8 - 4.0r_t + 5.0(r_t - 0.56)f_w & f_w \geq 0.8
    \end{cases}
    \]
- Dielectric constant:
  - Rain: Cole and Cole (1941)
  - Hail: Maxwell-Garnett mixing formula (water/ice)
- In the emulator, the model of Rasmussen and Heymsfield (1987) is used to determine the allowable water mass amount, allowing \( f_w \) to vary as a function of diameter
- Observations
  - Hail @ Sband >> Hail @ Xband
  - Wet hail can have appreciable \( Z_{DR} < 0 \) dB and \( K_{DP} < 0° \) km\(^{-1}\)
  - Not shown - backscatter differential phase (\( \delta \)) in hail at higher frequencies can be extremely variable and significant
Half-circle hodograph, $\alpha_r$

$D_{MH}$
Reasonable Expectations

- Potential limitations
  - Each species must still fit a gamma distribution (multimodal distributions cannot be simulated), may variably affect $Z_H$, $Z_{DR}$, and $\rho_{HV}$ when different processes affect different parts of the DSD
  - Very seldom is a BWER simulated
    - Perhaps related to the use of a bulk scheme instead of a spectral bin scheme (producing rain too quickly; Khain and Lynn 2009; Straka 2009).
  - Currently only one rain category being used
    - Would be more preferable to have multiple rain categories to account for, e.g., shedding from melting hail
Sounding

- Analytical sounding from Weisman and Klemp (1982)
- $\text{SBCAPE}_{TV}: 2078 \text{ J/kg}$
- $\text{SBCIN}_{TV}: -31 \text{ J/kg}$
- LCL: 833 m
- LFC: 1409 m
- Env. $0^\circ$C: $\sim 3800$ m
- Parcel $0^\circ$C: $\sim 4800$ m
- Very moist troposphere characteristic of the WK82 sounding (64 mm PW)
Hodographs

<table>
<thead>
<tr>
<th>Weak</th>
<th>Strong</th>
</tr>
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<tbody>
<tr>
<td>( \frac{\partial V_H}{\partial z} \approx 4.7 \times 10^{-3} , s^{-1} )</td>
<td></td>
</tr>
<tr>
<td>( \frac{\partial V_H}{\partial z} \approx 7.8 \times 10^{-3} , s^{-1} )</td>
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Half-Circle
\( Z_{DR} \) & \( \rho_{HV} \) Rings

\( \rho_{HV} \) ring primarily modeled coincident with very large hail aloft along the downshear side of the updraft.

ZDR half-rings seen near edge of updraft, comprised of hail and graupel with high fractional water content.
\( \rho_{HV} \) Rings

- Half-circle, “weak” shear example
- Number of gridpoints with low \( \rho_{HV} \)
  - S band: \( \rho_{HV} < 0.98 \)
  - X band: \( \rho_{HV} < 0.9 \)
- Number of gridpoints with \( D_{mh} > 5 \text{ mm} \)
- Generally much more obvious (larger, lower \( \rho_{HV} \)) at higher frequencies (e.g., X band).
$\rho_{HV}$ rings -> Hail at the surface?

- X Band
- Left: Area of X-band $\rho_{HV} < 0.9$ at $\sim 5600$ m and area of $qh > 0.001$
- Some “hail dumps” at the surface are preceded by increases in the size of the $\rho_{HV}$ rings aloft, but not all
- Half-circle, “strong” shear example
- X band shows greater sensitivity to large graupel and hail along
- Number of gridpoints with \( D_{mh} > 5 \) mm
- Generally much more obvious (larger, lower \( \rhoHV \)) at higher frequencies (e.g., X band).
Inner section primarily wet hail – low ZDR at S, high at X
Physical Insight – $Z_{DR}$ Column

Half-circle
“weak” shear
$Z \sim 5600$ m

$Z_{DR}$
$W$ cont.

FWH
$Z_{DR}$ cont.

$QH$
$Z_{DR}$ (cont)
Half-circle “weak”

Half-circle “strong”

Straight “weak”

Straight “strong”
Maximum Height of $Z_{DR} > 1$ dB

- 15_straight: ~6000 m
- 25_straight: Reminder: Freezing level of surface parcel ~4800 m AGL in sounding
- 15r10km: ~6500-7000 m
- 25r10km:

Reminder:
Freezing level of surface parcel ~4800 m AGL in sounding
**Z_{DR} Column Size**

- One simulation to the right
- Number of gridpoints with $Z_{DR} > 1$ dB vs. $W > 5$ m/s at z grid-point 25 (3800-3900 m)
- $R^2 = 0.85$

Each mark is from a 2-minute history file
- Domain-wide area of $Z_{DR} > 1$ dB vs. $W > 5$ m/s at z grid-point 25 (~3900 m AGL)
- In the aggregate, larger updraft yields larger $Z_{DR}$ column
- Correlation stronger with “weak” shear cases than “strong” shear cases
\[ R^2 = 0.48 \]

Area of Qr > 0.001
Area of Z_{DR} > 1 dB

\[ R^2 = 0.77 \]

Half-circle Hodograph

\[ W_{\text{max}} \]
Area of Z_{DR} > 1 dB
\[ R^2 = 0 \]

\[ R^2 = 0.84 \]

“Strong”
Area of Qr > 0.001
Area of Z_{DR} > 1 dB

“Weak”
Area of Qr > 0.001
Area of Z_{DR} > 1 dB

\[ W_{\text{max}} \]
Area of Z_{DR} > 1 dB
\[ R^2 = 0.48 \]
Poor correlations between $Z_{\text{DR}}$ column height or cross-sectional area and near-surface hail properties

- Area($Q_h > 0.0254 \text{ cm}$)
- Sum($Q_h$)
- Max($Q_h$)

The $Z_{\text{DR}}$ column in these runs is shorter than seen in more sophisticated modeling suites (e.g., Kumjian et al. 2012)

- Drops freezing too quickly
Reviewing the Guiding Questions

- The focus of this study is to expand our understanding of often-seen polarimetric signatures (in particular the $Z_{DR}$ and $K_{DP}$ columns and the $\rho_{HV}$ and $Z_{DR}$ rings)
  - What is the relationship between polarimetric signatures and kinematic, microphysical, and thermodynamic fields
  - What is the relationship between the evolution of these signatures to unobserved quantities
  - How does vertical wind shear affect the appearance and the evolution of these signatures

- Special Acknowledgments
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In general, upward protrusion of ZDR > 0 dB an KDP > 0 deg km^-1 above the ambient and upward-perturbed updraft freezing level is positively associated with the west / upshear part of the updraft.