The Dependence of Numerically Simulated Cyclic Mesocyclogenesis upon Environmental Vertical Wind Shear

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ABSTRACT

Building upon the authors’ previous work that examined the dynamics of numerically simulated cyclic mesocyclogenesis and its dependence upon model physical and computational parameters, this study likewise uses idealized numerical simulations to investigate associated dependencies upon ambient vertical wind shear. Specifically, the authors examine variations in hodograph shape, shear magnitude, and shear distribution, leading to storms with behavior ranging from steady state to varying degrees of aperiodic occluding cyclic mesocyclogenesis. However, the authors also demonstrate that a different mode of non-occluding cyclic mesocyclogenesis may occur in certain environments.

Straight hodographs (unidirectional shear) produce only nonoccluding cyclic mesocyclogenesis. Introducing some curvature by adding a quarter circle of turning at low levels results in steady, nonoccluding, and occluding modes. When a higher degree of curvature is introduced—for example, turning through half and three-quarter circles—the tendency for nonoccluding behavior is diminished. None of the full-circle hodographs exhibited cycling during 4 h of simulation. Overall, within a given storm, the preferred mode of cycling is related principally to hodograph shape and magnitude of the ambient vertical shear.

1. Introduction

The simulation study by Adlerman et al. (1999, hereafter A99) of multiple mesocyclones within a single classic supercell storm marked the first step toward understanding the dynamics that underlie the cyclic occlusion process. A99 proposed a sequence of five distinct stages of development and described how a fortuitous arrangement of flow structures promotes cyclic behavior. Building upon that study, Adlerman and Droegemeier (2002, hereafter AD02) examined the dependence of cyclic mesocyclogenesis upon model physical and computational parameters, noting clear and often dramatic changes in storm behavior resulting from nominal variations in grid spacing, computational mixing, surface friction, and cloud microphysics. As an extension of these works, the present study explores the role played by the ambient environment in delineating cyclic from noncyclic mesocyclones as well as the extent to which the environment influences the timing and character of mesocyclone occlusions.

Because numerical simulations (e.g., Weisman and Klemp 1982, 1984; Brooks et al. 1993; 1994), observations (e.g., Rasmussen and Straka 1998), and theory (e.g., Davies-Jones 2002) suggest that both hodograph shape and the magnitude of vertical environmental shear influence storm morphology, this study examines the dependence upon cyclic mesocyclogenesis of variations in the environmental wind profile. Although thermodynamic parameters also have a profound influence upon supercell character (e.g., Davies 2002), variations in CAPE are not examined here in order to keep the number of simulations reasonable. Therefore, multiple variations in hodograph shape, shear magnitude, and shear distribution are examined with the intent of identifying corresponding trends in cycling behavior.

This paper is organized as follows. Section 2 discusses the model and its configuration while section 3 explains the design of our parameter space. Section 4 describes
the control simulation, and sections 5–8 present results from the half-circle, straight, quarter-circle, three-quarter-circle, and full-circle hodographs, respectively. Finally, we summarize in section 9 the results and discuss their implications.

2. Model configuration

The simulations are conducted using version 5.0 of the Advanced Regional Prediction System (ARPS), a three-dimensional, nonhydrostatic prediction system developed for storm and mesoscale applications (Xue et al. 2000, 2001, 2003). Similar to A99 and AD02, the simulations are conducted using a horizontally homogeneous environment within which convection is initiated using an ellipsoidal thermal bubble. The computational grid has uniform horizontal spacing of 500 m within a 16 km domain, with 43 levels in the vertical. The vertical grid spacing varies smoothly from 100 m at the ground to 700 m near the top of the domain. This results in the lowest scalar grid point being located at a height of 50 m AGL, the level that we will interchangeably describe as “surface” or “near ground.”

Fourth-order advection is used in all directions for both scalar and vector fields. Cloud microphysics is treated using the Kessler (1969) warm-rain parameterization scheme, while subgrid-scale turbulent mixing is represented using a 1.5-order turbulent kinetic energy (TKE) closure. We have neglected ice physics in these simulations to ensure consistency with the control run in AD02, and because solution sensitivity to microphysics was examined in that paper. The Coriolis force, surface friction, surface physics, and terrain are not included. The model is integrated for 4 h and history files are saved every 5 min after 3300 s. A summary of model parameters is shown in Table 1.

Based upon the results of AD02, our use here of 500-m horizontal grid spacing likely results in a solution that is not numerically converged. Because numerical convergence and the correct representation of an inertial subrange probably require horizontal grid spacings less than 100 m (Bryan et al. 2003), it would be computationally unfeasible to conduct a large parameter study within such constraints. Although varying the grid spacing between 105 and 1 km in AD02 did change the speed of cycling, it did not fundamentally change storm morphology or the mode of cycling. Only when the grid spacing approached a size at which the mesocyclone no longer was well resolved (i.e., 2 km) did the solution exhibit a fundamental shift in behavior. Because the purpose of this study is to classify general trends in cycling based upon shear and hodograph shape, changes in grid spacing would not necessarily invalidate any of the results. More likely, they would merely shift the parameter space. Similarly, sensitivities to microphysics, numerical diffusion, and surface friction would likely also shift the parameter space, but leave the general findings valid (see AD02).

3. Parameter space

A wide range of shear structures and hodograph shapes has been used in previous deep convective storm
parameter studies (Weisman and Klemp 1982, 1984, 1986; Klemp and Weisman 1983; Brooks and Wilhelmson 1993; Brooks et al. 1993, 1994; Droegemeier et al. 1993; Jahn 1995; Gilmore and Wicker 1998; Weisman and Rotunno 2000; McCaul and Weisman 2001; McCaul and Cohen 2002), with only a few authors (Klemp and Weisman 1983; Weisman and Klemp 1986; Droegemeier et al. 1993) having used a broad range of hodograph shapes and shear magnitudes in a single study. Almost all previous parameter studies have been based upon an analytic sounding similar or identical to that used by Weisman and Klemp (1982), which contains an almost tropical moisture profile and is arguably limited in its relevance to continental deep convective storms. Variations in the ambient vertical temperature profile have been very limited until the recent work of McCaul and Weisman (2001) and McCaul and Cohen (2002).

The construction of a broad, physically realistic parameter space that varies in a controlled manner is a notable challenge (e.g., Richardson 1999) for which no unique approach exists. Our strategy involves the use of canonical hodograph shapes, to which systematic variations are applied in the magnitude and vertical distribution of the shear. The control run is based upon the half-circle hodograph because it represents an idealization of our previous simulations and has been used extensively in other studies. We then include straight, quarter-circle (with and without additional rectilinear shear), three-quarter-circle, and full-circle hodographs (Fig. 1), the specific attributes of which are described below. Only simulations that yield supercell storms (defined in section 5) are considered because mesocyclones are uniquely associated with this storm type. Although some of the hodographs used in our final simulations might be considered unrealistic due to their shape or magnitude of shear, they were included in order to completely cover the parameter space, similar to the strategy of Droegemeier et al. (1993).

As in our previous simulations (A99; AD02), the horizontally homogeneous model base state is initialized using a composited thermodynamic profile (Fig. 2) associated with the well-documented 20 May 1977 Del City, Oklahoma, storm (e.g., Ray et al. 1981; Johnson et al. 1987). This profile has a CAPE of 2673 J kg$^{-1}$, calculated using the virtual temperature correction and accounting for water loading. When calculated without these modifications, the CAPE is 3777 J kg$^{-1}$. In all further discussions, the uncorrected method of calculation will be used because it is consistent with the definition of the bulk Richardson number (BRN; Weisman and Klemp 1982).

A listing of model environmental parameters associated with all experiments is shown in Table 2. The run name abbreviation and description are shown in the first two columns, followed by the CAPE value. Both 0–6-km BRN shear (hereafter BRNsh$_6$; Weisman and Klemp 1982) and 0–9-km BRN shear (hereafter...
BRNsh, Rasmussen and Straka 1998) are also calculated, along with their corresponding BRN values, BRN and BRN, respectively. The next columns display the storm-relative helicities (SRH; Davies-Jones et al. 1990) calculated in the 0–1-km layer (hereafter SRH1) and the 0–3-km layer (hereafter SRH3). To compute these values an average domain speed that kept the storm approximately stationary after the first hour of simulation is used.1 For comparison, an estimated SRH is also calculated a priori using a storm motion estimated from the method of Davies and Johns (1993). Last, a storm-relative surface inflow is calculated using the previously mentioned average domain speed and the surface wind from the sounding.

4. Nomenclature and the control experiment

a. Nomenclature

Before describing results from the control simulation, several clarifications are in order regarding the nomenclature of cyclic supercell storms. First, we define the moment of “occlusion” as the time when a

1 Several tests were performed in which SRH was also calculated every 15 min using a storm motion manually derived from updraft location at 4 km. When this time series was averaged, the SRH values were very similar (within ~10%) to those derived using the domain motion.
Table 2. Summary of the model soundings and their derived parameters. SRH values are calculated from an average domain speed used to keep the storm of interest nearly stationary. SRH values in parentheses are estimated from the sounding using the method of Davies and Johns (1993).

<table>
<thead>
<tr>
<th>Simulation abbreviation</th>
<th>Description</th>
<th>CAPE (J kg(^{-1}))</th>
<th>BRN(_{sh}) (m s(^{-1}))</th>
<th>BRN(_a) (m s(^{-1}))</th>
<th>BRN(_g)</th>
<th>SRH(_1) (m(^2) s(^{-2})) actual (estimate)</th>
<th>SRH(_3) (m(^2) s(^{-2})) actual (estimate)</th>
<th>SR surface inflow (m s(^{-1}))</th>
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<td>Control</td>
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<td>42</td>
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<td>87 (73)</td>
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<td>67</td>
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<td>55 (50)</td>
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<td>15.9</td>
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<td>Control, with shear shifted upward</td>
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<tr>
<td>Simulation abbreviation</td>
<td>Description</td>
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<td>BRNshₐ (m s⁻¹)</td>
<td>BRNₐ (m s⁻¹)</td>
<td>BRNshₐ actual (estimate)</td>
<td>SRH₂ (m² s⁻²) actual (estimate)</td>
<td>SRH₃ (m² s⁻²)</td>
<td>SR surface inflow (m s⁻¹)</td>
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<td>Quarter circle, $r = 15$ m s⁻¹ from 0 to 1 km, tail length 60 m s⁻¹ from 1 to 9 km</td>
<td>3777</td>
<td>26.1</td>
<td>11</td>
<td>34.5</td>
<td>6</td>
<td>533 (395)</td>
<td>824 (527)</td>
</tr>
</tbody>
</table>
near-ground mesocyclone becomes detached from the gust front and downdraft air wraps completely around it (Fig. 3). This is consistent with the descriptions in A99 and AD02. By definition, an occlusion separates two distinct cycles within a single storm that is undergoing occluding cyclic mesocyclogenesis (OCM). With this convention, a storm undergoing four cycles must occlude three times. During a particular cycle, the storm’s near-ground mesocyclone may strengthen and weaken with both periodic and/or pulsating behavior. As long as the mesocyclone does not completely dissipate and reform in a different location, such behavior is still classified as a single distinct cycle.

Second, we define nonoccluding cyclic mesocyclogenesis (NOCM) as the repeated development of near-ground mesocyclones that do not go through an occlusion process as part of their weakening and dissipation phases. Oftentimes NOCM occurs when near-ground mesocyclones move down the gust front, and away from the main updraft, rather than wrapping back into the precipitation core. They then become separated from the main updraft and a new mesocyclone forms farther northward, near the forward-flank precipitation boundary (Fig. 3).

Both OCM and NOCM may occur within a single storm. To avoid confusion, all references to “occlusions” denote OCM. References to “cycles” will be clarified as OCM cycles (i.e., “occlusion cycles”) or NOCM cycles (i.e., “nonocclusion cycles”). In addition, all cycling schematics will use different representations for OCM and NOCM, with NOCM cycles notated as “Meso 1,” “Meso 2,” etc.

b. The control experiment

To establish a control hodograph in which the vertical shear can be modified easily, it is useful to develop...
Fig. 3. Schematic of the approximate surface patterns for occluding and nonoccluding cyclic mesocyclogenesis. Scalloped black line indicates the surface cold-pool boundary. Red indicates area of vorticity maxima. Light blue indicates updraft areas, and dark blue indicates downdraft areas. Single yellow contour indicates the boundary of the rain area.

Fig. 4. Hodograph from the original 20 May 1977 Del City case (diamond points; Ray et al. 1981) and the idealized half-circle hodograph (triangle points) with a radius of 19 m s\(^{-1}\) and a turning depth of 10 km.
Fig. 5. Plots of (left) rainwater mixing ratio and vertical velocity at (center) \( z = 50 \) m and (right) \( z = 4.5 \) km for the control run at (a) 5700, (b) 6600, (c) 7200, (d) 7800, and (e) 8400 s. Negative vertical velocity contoured in light blue at an interval of (center) 0.3 and (right) 5.0 m s\(^{-1}\). Vertical vorticity contoured in black at irregular intervals 0.01, 0.02, 0.035, and 0.05 s\(^{-1}\). Single dark blue contour indicates 1 g kg\(^{-1}\) rainwater mixing ratio. Axes labeled in km. Grid-relative wind vectors indicated.
an idealization of the Del City wind profile. After rotating the original Del City hodograph by 15°, recentering, and estimating its termination point at 10 km, the Del City hodograph may be approximated by a half-circle hodograph of radius 19 m s⁻¹ (Fig. 4), with uniform shear throughout the depth of turning (0–10 km). This yields a BRNsh_6 and BRNsh_9 of approximately 13.4 and 17.5 m s⁻¹, respectively, compared to 12.3 and 15.5 m s⁻¹ for the original Del City hodograph.

When this idealization of the Del City hodograph and associated thermodynamic profile (Fig. 2) are used to initialize the model the resulting control simulation (Fig. 5) is remarkably similar, though not perfectly identical to that reported in AD02 (which used the actual Del City hodograph). The principal storm develops into a mature supercell by 3600 s, with a pronounced hook and strong near-ground mesocyclone evident by 4200 s. The first occlusion cycle begins after 6600 s, marked by the development of a dual updraft structure and an occluded surface gust front. Near-ground vorticity peaks at 7200 s, and the first occlusion occurs shortly thereafter, with the development of a new near-ground mesocyclone clearly underway by 7800 s.

The second occlusion cycle proceeds similar to the first. Near-ground vorticity peaks in the occluding mesocyclone at 11 400 s and the occlusion occurs at approximately 12 000 s. A new mesocyclone develops once again to the east, and the storm continues without another occlusion evident through the end of the simulation (14 400 s). Most experiments described subsequently are compared to this control run.

5. Half-circle hodograph simulations

a. Uniform shear distribution over 10 km

In examining variations of the environmental wind profile, we begin with a half-circle hodograph that extends over a depth of 10 km in order to maintain similarity with the control simulation. Four experiments are conducted with shear uniformly distributed over the turning depth. Radii of 15, 25, 30, and 35 m s⁻¹ are used, and the simulations are designated Half_r15, Half_r25, Half_r30, and Half_r35, respectively. Environmental parameters for these experiments are presented in Table 2, and a summary of physical mechanisms is deferred until all results have been presented.

As mentioned previously, all of the simulations considered produce supercell storms. In the context of this study, we assume that a supercell 1) remains relatively isolated and distinct throughout the length of the simulation—that is, it does not exhibit classic multicellular behavior, become embedded within a line, or interact with other convective elements; and 2) contains a mesocyclone that exhibits time and height continuity from at least midlevels (around 4 km) and above with vertical vorticity of at least 0.01 s⁻¹. All storms meeting these criteria also possessed some form of hook appendage in the rainwater field, although with large variations in size and shape.

A hodograph radius of 10 m s⁻¹ did not produce a sustainable storm, apparently a result of the 0–3-km storm-relative inflow being less than 10 m s⁻¹ (Droege-
meier et al. 1993). (The control simulation has a radius of 19 m s$^{-1}$, thereby placing it between Half_r15 and Half_r25.) The effects of hodograph radii changes are quite varied, but they clearly suggest that increasing the magnitude of the vertical shear throughout the same depth of turning tends to slow down and eventually terminate the cycling process. A summary of cycling characteristics is shown in Fig. 6. Half_r15 produces a small supercell that appears to be a miniature version of the one in the control run. It undergoes three full OCM cycles, with the first and second occlusions delayed by approximately 300 s relative to the control run. Half_r25 produces a storm that appears very similar to that in the control run, except that it has a stronger near-ground mesocyclone and occludes only once (at 9600 s).

Experiments Half_r30 and Half_r35 both produce supercell storms that are much larger in areal extent than in the control run and do not cycle throughout the entire simulation period (Fig. 6). Differences in updraft size and rainwater area between the lowest and highest shear cases (Half_r15 and Half_r35) are quite striking (Fig. 7) and have been noted in other studies (e.g., Droegemeier et al. 1993). The areal extent of rainwater at $z = 50$ m increases from approximately 120 to 840 km$^2$, 

![Simulation Half_r15](image1.png)

![Simulation Half_r35](image2.png)

Fig. 7. Plots of (left) rainwater mixing ratio at $z = 50$ m and (right) vertical velocity at $z = 4.5$ km (color filled) for simulations (top) Half_r15 and (bottom) Half_r35 at $t = 11700$ s. Negative vertical velocity contoured in light blue at an interval of 3 m s$^{-1}$. Axes labeled in km. Grid-relative wind vectors indicated.
while that of the updraft at $z = 4.5$ km increases from approximately 60 to 360 km$^2$. These effects may result from inhibited turbulence dissipation in the most helical flows (Kraichnan 1973; Andre and Lesieur 1977; Lilly 1986; Teabeault 1998).

Toward the end of the integration period, simulations Half_r30 and Half_r35 exhibit quite different supercell structures from one another. Similar to the other cases, Half_r35 remains quite “classic” throughout its lifetime. In contrast, Half_r30 takes on features characteristic of a “high precipitation” (HP) storm (Moller et al. 1994), with increasing amounts of rain wrapping around the upshear side of the mesocyclone. By 12 300 s, its updraft and gust front begin to stretch out into a nearly north–south orientation and the storm appears to be transitioning toward a more outflow-dominated mode (Fig. 8).

In summary, simply changing the radius of the control run hodograph over a fixed depth results in a relatively orderly progression of cyclic behavior. Namely, as the radius and thus overall shear magnitude increase, the OCM cycles decrease in number and are delayed. At sufficiently high shear ($\text{BRN}_{\text{sh}} = 21.2$ m s$^{-1}$), the storm transitions to a noncycling supercell. Further, overall storm area increases markedly with increasing shear magnitude.

b. Variations in shear distribution over 10 km

To explore the effects of changes in the vertical distribution of vertical shear, we systematically shift the location of wind altitude points along the arc of the control hodograph. Using a hyperbolic tangent function that also is used for vertical grid stretching

$$\Delta z(i) = \Delta z_{\text{av}} + \frac{\Delta z_{\text{min}} - \Delta z_{\text{av}}}{\tanh(2a)} \tanh \left[ \frac{2\alpha}{1 - a}(i - a) \right]$$

for $i = 1, 2, 3, \ldots, (nz - 3)$ (1)

in the ARPS (Xue et al. 1995; AD02), we transform the uniform vertical distribution of environmental wind data points either downward or upward, thus increasing (decreasing) upper- (lower-) level shear or decreasing (increasing) upper- (lower-) level shear. This methodology preserves both the shape of the hodograph and the mean shear ($6 \times 10^{-3}$ m s$^{-1}$), that is, the length of the hodograph divided by the depth of turning (Rasmussen and Wilhelmson 1983).

Eight simulations are conducted using this strategy, four in which the low-level shear is increased (Shift_L1, Shift_L2, Shift_L3, and Shift_L4) and four in which the upper-level shear is increased (Shift_U1, Shift_U2, Shift_U3, and Shift_U4). Shift_L1 has the strongest low-level shear and Shift_U4 has the weakest (Fig. 9). Despite some values of SRH$_3$ and BRN$_6$ (Table 2) that would usually suggest multicellular convection (e.g., Shift_U4), all simulations display clear supercell characteristics.

A summary of the cycling characteristics is shown in Fig. 10. As the low-level shear is increased, the OCM cycling process slows significantly for simulations Shift_L3 and Shift_L2, eventually ceasing entirely in the simulation with the strongest low-level shear, Shift_L1. Compared to the control run, the first and second occlusions are delayed 2100 s for Shift_L3. In Shift_L2, the first occlusion is delayed by 4500 s, and no second OCM cycle is observed.

For Shift_U2 through Shift_U4, an opposite progression in the timing of the OCM cycles is observed, with...
mesocyclone cycling slowing as the low-level shear weakens and the upper-level shear increases, eventually ceasing for Shift_U4 (Fig. 10). However, Shift_U1 exhibits no cycling, with the storm persistently exhibiting an occluded structure for the duration of the simulation (Fig. 11). Because this behavior seemed unusual and countered trends in other cases, two additional hodographs were constructed, Shift_U1a and Shift_U1b, each varying only slightly from Shift_U1 (Table 2). The differences in BRNsh6 and SRH3 are less than 0.8 m s⁻¹ and 16 m² s⁻², respectively. The storms in these two additional simulations do cycle slightly more slowly than those in the control run, thus fitting well into the pattern of cycling variations displayed in Fig. 10. Because the storm structures are all quite similar, this sensitivity is puzzling but not surprising given previously demonstrated sensitivities (AD02). However, it does suggest that comparable sensitivities in the context of actual prediction could be remedied by an ensemble approach (e.g., Hou et al. 2001). Although an ensemble mean for convective storms might be of questionable value (Levit et al. 2004), conditional probabilities appear to be exceptionally useful.

In summary, either increasing the low-level shear

![Fig. 9. Hodographs for simulations (left) Shift_L1 and (right) Shift_U4.](image)

![Fig. 10. Schematic of cycling behavior for the shift simulations. Dotted bar indicates the anomalous Shift_U1 run.](image)
while reducing the upper-level shear, or increasing the upper-level shear while reducing the low-level shear, has the same effect of reducing the number of occlusion cycles and delaying their timing. Between these two extremes, there exists a fairly orderly progression of occlusion behavior that regresses back toward the control run, although some anomalous sensitivities are observed.

c. Uniform shear distribution over 6 km

To examine the effect of confining the turning layer to a shallower depth (6 km), five additional half-circle hodograph simulations are conducted with the shear still uniformly distributed within this layer. The radii are chosen such that each simulation has the same corresponding mean shear as the previous half-circle runs (i.e., Half_r15 through Half_r35, including the control run), giving respective radii of 9, 11, 15, 18, and 21 m s\(^{-1}\) (Table 2). The simulations are designated Half6_r9, Half6_r11, Half6_r15, Half6_r18, and Half6_r21, respectively.

Similar to Half_r15 (Fig. 7), Half6_r9 produces a supercell that is quite small in areal extent (e.g., the updraft at 4.5 km covers approximately 42 km\(^2\)). However, it does not cycle throughout the entire simulation (Fig. 12), and its near-ground mesocyclone remains relatively weak when compared to that in the control run. Simulations Half6_r11 and Half6_r15 produce OCM cyclic supercells that qualitatively resemble those in the control case but cycle more slowly (Fig. 12). Compared to the control run, the first occlusions for Half6_r11 and Half6_r15 are delayed by 1200 and 3000 s, respectively. The second occlusions are delayed by 2400 and 2100 s, respectively. Simulation Half6_r18 also

![Fig. 11. Comparison of vertical velocity for the (top) control run and (bottom) Shift_U1 at (left) t = 7500 s and (right) t = 8700 s. Light blue contour indicates negative vertical velocity, contoured at an interval of 0.2 m s\(^{-1}\). Dark blue contour indicates 1 g kg\(^{-1}\) rainwater mixing ratio. Vertical vorticity is contoured in black at an interval of 0.02 s\(^{-1}\) m\(^{-1}\). Axes labeled in km. Grid-relative wind vectors indicated.](image-url)
produces an OCM cyclic supercell, but similar to Half_r30, it takes on a more HP character toward the end of the run. It undergoes its first occlusion at approximately the same time as the control run (7800 s), but its second occlusion is delayed to 14 400 s, or 2400 s later than the control (Fig. 12).

In the highest shear simulation, Half6_r21, the process of cyclic mesocyclogenesis occurs in an unusual NOCM that is not evident in any of the other half-circle hodograph simulations. The first mesocyclone and associated hook (Figs. 13a–c) form as in the control run, with a strong vorticity maximum (A) extending from the surface upward through 4-km altitude at 7800 s. However, because the surface winds behind the gust front remain mostly northerly (Figs. 13b,e) the near-ground mesocyclone does not occlude but instead travels southward down the gust front. As the midlevel updraft also develops farther southward (Fig. 13f), the mesocyclone center at 4 km remains well correlated with the near-ground mesocyclone. At the same time, however, a new near-ground mesocyclone develops farther north along the gust front, with a new midlevel mesocyclone (B) also apparent (Figs. 13d–f). As this new near-ground and midlevel mesocyclone move farther south (Figs. 13g–i), the old one dissipates. The remaining near-ground vorticity maximum moves southwestward and can be seen as a cyclonic flare in the rainwater contour (Figs. 13d,g). Throughout this transition the updraft never takes on a dual-maxima appearance (A99), but remains unicellular, with the maxima shifting northward with time. This type of NOCM cyclic regeneration occurs again at 11 100 and 11 700 s (Fig. 12), after which the storm takes on HP characteristics.

In summary, when the ambient shear is confined to a shallower depth in the half-circle hodograph simulations, cycling behavior becomes slightly less regular than in the previous results. Similar to the experiments in which the vertical distribution of shear was altered, the storm no longer occludes for the lowest shear (BRNsh_{6}/H1100 = 9.0 m s^{-1}) in the shallower depth cases. At intermediate shears, OCM occurs but without any clear trends in timing. At the highest shear (BRNsh_{6} = 21 m s^{-1}) storm behavior transitions to NOCM.

6. Straight-hodograph simulations

The straight hodograph represents one extreme of vertical wind shear structure in the ambient storm environment. Because linear shear-induced propagation cannot move an updraft off a straight hodograph, nonlinear rotationally induced propagation must dominate (Davies-Jones 2002). Storm splitting is required, and mirror-image updrafts propagate away from one another. Therefore, because the dynamics induced by a straight hodograph are fundamentally different from those of a highly curved hodograph, it is appropriate to consider straight hodographs in this study.

Four straight-hodograph simulations are conducted, with the shear linearly distributed from 0–10 km and the lengths of the hodographs chosen such that they have the same mean shear as simulations Half_r15...
This results in hodograph lengths of 47, 60, 79, and 94 m s\(^{-1}\), and the simulations are designated Straight_47, Straight_60, Straight_79, and Straight_94, respectively. [Hodographs using the hyperbolic tangent profile of Weisman and Klemp (1982) produced qualitatively similar storms.] Simulations Straight_79 and Straight_94 fall under the category “severely sheared storms” as described by Marwitz (1972).

Remarkably, none of the straight-hodograph simulations occlude during the 4-h simulation time. However, all of the simulations do undergo the same type of NOCM evident in Half6_r21 (section 5c) and in some of the quarter-circle simulations (section 7). This behavior is unique as the straight hodograph experiments are the only ones in which every simulation displays this same behavior, an example of which is shown in Fig. 14 for Straight_47. Storm morphology is qualitatively similar to that displayed in Half6_r21 (Fig. 13).

Figure 15 shows the entire life cycle of each moderately strong (near-ground vertical vorticity \(0.02 \text{ s}^{-1}\)) near-ground mesocyclone for the straight-hodograph simulations. There is little discernible regularity to the pattern of cycling for these NOCM cases. However, two general trends are apparent. First, it appears that the lifetime of each mesocyclone decreases as the magnitude of the shear increases. This is quite opposite to the trend
demonstrated previously, namely, that increasing shear tended to slow OCM cycling. However, because the grid-relative flow behind the gust front in the straight-hodograph cases is nearly parallel to the front, the increasing shear tends to increase the frequency at which the near-ground mesocyclone is forced away from the main updraft. Second, similar to most of our previous results and consistent with stronger storm-relative inflow, the time of initial mesocyclone cycling is slowed with increasing shear magnitude.

7. Quarter-circle simulations

a. 3-km turning depth

The quarter-circle hodograph is unique for two reasons. First, it represents the best approximation to the average observed supercell sounding (e.g., Chisholm and Renick 1972; Doswell and Evans 2003), although Davies-Jones (2003) has recently criticized this finding because the curvature of a mean hodograph does not necessarily equal the mean of the individual curvatures. Second, the quarter-circle hodograph easily allows for independent analytic variations in the upper- and lower-level shear.

With this in mind, three sets of quarter-circle hodograph simulations are conducted, one each with radii of 10, 15, and 20 m s\(^{-1}\). In this section, the depth of turning is kept constant at 3 km, with westerly rectilinear shear from 0 to 60 m s\(^{-1}\) distributed over altitudes from 3 to 9 km. Sixteen hodographs of this type are used, each named according to the convention Qtr3_RRSS, where RR is the radius and SS is the
“magnitude” [hodograph length (m s$^{-1}$)] of the rectilinear shear (Table 2). The complete set of profiles is shown in Table 2.

A summary of cycling characteristics for the quarter-circle simulations of radius 10 m s$^{-1}$ (Qtr3_10, Table 2) is shown in Fig. 16. For the lowest shear case, Qtr3_1000, the simulation produces a very small (i.e., the areal extents of the updraft at 4.5 km and q$_r$ at 35 m are only 24 and 128 km$^2$, respectively) noncycling supercell despite values of BRN and SRH that might suggest a multicellular storm. However, the associated mesocyclone remains fairly weak throughout the run, with near-ground vorticity never exceeding 0.03 s$^{-1}$. As the rectilinear shear is increased (i.e., above 3 km), the simulated storms begin to cycle (OCM). In Qtr3_1010, two OCM cycles occur with an occlusion at approximately 11 400 s (Fig. 17). When the rectilinear shear is increased to 20 m s$^{-1}$ in Qtr3_1020, three OCM cycles are observed, with the first occlusion occurring approximately 3600 s earlier than in Qtr3_1010 (Fig. 17). When the rectilinear shear is increased further for Qtr3_1040, mesocyclone cycling slows and only one occlusion is observed at 12 000 s.

A transition in the mode of cycling occurs when the rectilinear shear is increased to its highest value of 60 m s$^{-1}$ (higher than what might realistically be observed in a severe storm situation) for Qtr3_1060. Although a classic occlusion occurs at 8100 s, the storm undergoes NOCM during the remainder of its lifetime, with near-ground mesocyclones repeatedly forming farther north along the gust front. This behavior is similar to that of Half6_r21 (section 5c; Fig. 13) except that in Qtr3_1060,
the cycling is more rapid, with a somewhat remarkable six near-ground mesocyclones observed during the 4-h simulation (Fig. 16).

Overall, the pattern of cycling for the Qtr3_10 simulations is similar to that of the Half6 simulations (section 5c; Fig. 12). At very low shear, no cycling is evident. As the shear increases, OCM cycling commences. Then, at high shear, the storm transitions to NOCM.

An increase in the radius of the quarter circle to 15 m s\(^{-1}\) (simulations Qtr3_15, Table 2) produces more varied cycling behavior (Fig. 17). In the lowest shear simulation, Qtr3_1500, two OCM cycles occur, with the occlusion taking place at approximately 8100 s. When the rectilinear shear is increased to 20 m s\(^{-1}\), the storm undergoes two occlusions, the first approximately 1200 s later than in Qtr3_1500. However, when the rectilinear shear is only 10 m s\(^{-1}\), the storm changes cycling modes and undergoes NOCM after 10 800 s. Because this behavior is anomalous compared to surrounding simulations in the parameter space, two additional simulations are conducted with rectilinear shear of 5 and 15 m s\(^{-1}\). Similar to Qtr3_1500, both Qtr3_1515 and Qtr3_1505 undergo two OCM cycles, with the first occlusion occurring from 300 to 900 s later than in Qtr3_1520 (Fig. 18). Therefore, this sensitivity seems to be an isolated event similar to that encountered in Shift_U1 (section 5b).

When the rectilinear shear is increased to 40 and 60 m s\(^{-1}\) in Qtr3_1540 and Qtr3_1560 (Fig. 18), respectively, the simulated storms again transition to a rapid mode of NOCM, similar to that simulated in

**Fig. 13. (Continued)**
Four mesocyclones occur in Qtr3_1540 while six develop in Qtr3_1560. There again appears to exist a tendency for more rapid NOCM cycling with increasing shear in this case, a trend that is opposite to that in many of the OCM cyclic cases but consistent with our straight-hodograph simulations.

When the radius of the quarter-circle hodograph is increased to 20 m s$^{-1}$ (simulations Qtr3_20, Table 2), the mode of cycling transitions to almost entirely NOCM. A summary of these cycling characteristics is shown in Fig. 18. Three mesocyclones are produced in Qtr3_2000, while Qtr3_2010 yields six. As the rectilinear shear is further increased (Qtr3_2020 through Qtr3_2060, Fig. 18), the number of simulated mesocyclones decreases and the initial and subsequent mesocyclones are delayed. This behavior is similar to that found in many of the other simulations (e.g., sections 5 and 8). Unlike the Qtr3_15 cases, there does not appear to be a trend for more rapid NOCM cycling with increasing shear (or else the trend is confined to the Qtr3_2000-Qtr3_2010 simulations).

In summary, these quarter-circle hodographs produce relatively irregular cycling behavior, with both OCM and NOCM occurring. However, the results do suggest that both very low and very high shears tend to inhibit cycling except in cases where the storm transitions to NOCM at high shear. When NOCM becomes the dominant mode, initial and subsequent mesocyclones decreases and the initial and subsequent mesocyclones are delayed. This behavior is similar to that found in many of the other simulations (e.g., sections 5 and 8). Unlike the Qtr3_15 cases, there does not appear to be a trend for more rapid NOCM cycling with increasing shear (or else the trend is confined to the Qtr3_2000-Qtr3_2010 simulations).

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Fig. 14. Plots of vertical velocity (color filled) at $z = 50$ m for simulation Straight_47 at (a) 9000, (b) 9600, (c) 10 200, and (d) 10 800 s. Negative vertical velocity contoured in light blue at an interval of 0.2 m s$^{-1}$. Vertical vorticity contoured in black at an interval of 0.01 s$^{-1}$. Dark blue contour indicates $1$ g kg$^{-1}$ rainwater mixing ratio. Successive mesocyclones indicated by “A” and “B.” Axes labeled in km. Grid-relative wind vectors indicated.
appear to be delayed with increasing shear, similar to OCM.

b. 1-km turning depth

Recent studies (e.g., Craven et al. 2002; Brooks and Craven 2002; Rasmussen 2003) suggest that the 0–1-km shear and/or SRH is important in differentiating between environments that support tornadic versus non-tornadic supercells. To briefly examine the effects of confining the quarter-circle shear to this shallower depth, even though our simulations are not capable of addressing this specific question, a second set of quarter-circle experiments is undertaken using turning radii of 10, 15, and 20 m s\(^{-1}\) (Table 2). However, the depth of turning is kept constant at 1 km, with levels of westerly rectilinear shear from 20 to 60 m s\(^{-1}\) distributed over the vertical layer 1–9 km. Similar to the previous runs, each simulation is named according to the convention Qtr1_RRSS, where RR is the radius and SS is the length of the rectilinear shear. Unlike many of our

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**Fig. 15.** Schematic of cycling behavior for the straight simulations.

**Fig. 16.** Schematic of cycling behavior for the Qtr3_10 simulations.
other hodographs, this configuration confines most of the SRH to the 0–1-km layer (Table 2).

Figure 19 summarizes the cycling characteristics of the Qtr1 simulations. Experiment Qtr1_1020 maintains a weak near-ground mesocyclone throughout much of the integration period until it undergoes an occlusion at approximately 14 100 s. In Qtr1_1040, NOCM occurs between 8100 and 8400 s, followed by an occlusion at 12 600 s. However, thereafter the storm remains disorganized with no near-ground mesocyclone. Qtr1_1020 and Qtr1_1040 are the only Qtr1 simulations that exhibit OCM. Qtr1_1060 produces NOCM between 6600
and 7200 s, after which it remains quasi-steady, that is, possessing a single strong near-ground mesocyclone that fluctuates in intensity.

The principal storm in Qtr1_1520 remains fairly weak and disorganized throughout the simulation, with only two near-ground mesocyclones developing during the entire simulation. Storms in Qtr1_1540 and Qtr1_1560 behave similarly to those in Qtr1_1060, with one to two NOCM cycles followed by a transition to a quasi-steady supercell with a strong near-ground mesocyclone.

Simulations Qtr1_2020, Qtr1_2040, and Qtr1_2060 behave similarly, with no near-ground mesocyclone development until after 2 h of simulation time (although a single dominant storm is present). Once the near-ground mesocyclone develops, it remains present until the end of the simulation with no cycling or occlusions. This appears to result from the extremely strong low-level shear present in this set of hodographs, consistent with the simulations in section 5b.

It is of interest to note that the Qtr1 simulations produce the strongest near-ground mesocyclones of all experiments shown in Table 2, consistent with their large values of SRH and streamwise vorticity in the lowest 1 km. During their final cycles, simulations Qtr1_1040, Qtr1_1060, Qtr1_1540, Qtr1_1560, Qtr1_2040, and Qtr1_2060 all contain near-ground vorticity maxima in excess of $140 \times 10^{-3}$ $\text{s}^{-1}$, with approximate storm-relative winds in excess of 60 m s$^{-1}$ surrounding the near-ground mesocyclone. Experiment Qtr1_2060 produces a near-ground mesocyclone that is in approximate cyclostrophic balance, with a 58-hPa pressure drop across a horizontal extent of 5 km and surface winds of 71 m s$^{-1}$.

In summary, when the shear is confined to a shallower depth of 1 km in comparison to all other experiments, the quarter-circle hodographs again produce relatively irregular cycling behavior, with both OCM and NOCM occurring. Because the rectilinear shear now extends over a greater depth, those simulations with the smallest amount of rectilinear shear appear to be negatively influenced by the smaller magnitude of storm-relative winds. However, those with larger amounts of rectilinear shear produce extremely strong near-ground mesocyclones. If one assumes that a significantly stronger near-ground mesocyclone is more likely to produce a tornado, this result is consistent with trends observed in observations of supercell environments (Craven et al. 2002; Brooks and Craven 2002; Rasmussen 2003). Last, similar to our results in the previous section, when NOCM becomes the dominant mode, initial and subsequent mesocyclones appear to be delayed with increasing shear.

8. Three-quarter- and full-circle-hodograph simulations

Three-quarter-circle hodographs have been used only occasionally in storm simulations (e.g., Droegemeier et al. 1993) and represent the approximate upper limit of what might be observed in an environment sup-
portive of supercells [e.g., McCaul's (1993) close-proximity hurricane supercell hodograph is more akin to a three-quarter circle rather than a full circle]. The full-circle hodograph represents a more extreme case in which the environmental vorticity is almost purely streamwise at all heights within the turning depth. Since both are relatively uncommon, they will only be briefly described here.

Four sets of three-quarter-circle hodograph simulations are conducted: 3qtr_r15, 3qtr_r19, 3qtr_r25, and 3qtr_r30, with respective radii of 15, 19, 25, and 30 m s$^{-1}$ (Table 2). In all cases, the depth of turning is set to 10 km, similar to that of the half-circle simulations. The morphologies of storms in the three-quarter-circle simulations remain qualitatively similar to those of the control run. A summary of the simulations is shown in Fig. 20. The three-quarter-circle simulations show cycling trends similar to those of the half-circle simulations, and they again clearly suggest that increasing shear throughout the same depth of turning tends to slow down and eventually terminate the OCM cycling process.

Three full-circle ($360^\circ$ of turning) hodograph simulations are conducted. In each, the depth of turning is kept constant at 10 km, with radii of 15, 19, and 25 m s$^{-1}$ (Table 2). The simulations are designated 360_r15, 360_r19, and 360_r25, respectively. None of the full-circle simulations produces OCM or NOCM storms during the 4-h integration period. Despite the high values of SRH and BRNsh, it appears that circular shear has a detrimental effect upon storm morphology, resulting most likely from the unnatural redistribution of precipitation that causes storms to rain into their inflow.

9. Summary and discussion

Our experiments indicate that the mode and character of mesocyclone cycling depends upon the shape of the hodograph and the vertical distribution and magnitude of the vertical shear. Although the behavior is quite complex and sometimes irregular, we generalize some of our findings in the schematic shown in Fig. 21, which shows the mode of storm behavior (steady, OCM, NOCM) as a function of hodograph shape and a generalized measure of vertical shear. Because we have shown that the distribution and location of vertical environmental shear can radically alter storm morphology, we assume this generalized shear to be some average quantification of shear throughout the lower to upper troposphere, for example, the product of BRNsh and SRH$_1$. Overlapping boundaries in the parameter space indicate locations where multiple modes of cycling were present. However, because we have shown the existence of significant sensitivities to the environmental sounding, the boundaries between regions should be regarded as an approximate result rather than a fixed transition among cycling modes. In Fig. 21, values of BRNsh, SRH$_1$, and SRH$_3$ are shown at the appropriate location for many of the simulations. Figure 22 depicts the mean vertical velocity maxima and mean low-level ($<2$ km) vertical vorticity maxima for the same simulations. Although these numbers are do-
mainwide, they are calculated only during the time period of 3600–14 400 s, and thus the left-moving storms are out of the domain by the beginning of this interval.

Figure 21 shows that straight-hodograph simulations always produce storms that undergo NOCM. When we introduce a quarter-circle hodograph with rectilinear shear, all three modes of behavior occur. At very low shears, the storms tend to be steady or exhibit OCM, while at intermediate and higher shears, they tend to exhibit NOCM.

For half-circle hodographs, the tendency for NOCM is diminished, and in most cases, steady behavior is obtained at both very low shear and at high shear, with OCM in between. This trend continues for the three-quarter-circle hodographs, with steady behavior again observed at higher shears. Finally, the full-circle hodographs exhibit noncycling behavior during the control period.

Figure 22 suggests that, in general, the strongest mesocyclone rotational intensity occurs when the largest shears are confined to the shallowest depths (e.g., the Qtr1 and Half6 simulations). The strongest mesocyclones exhibit NOCM and the weakest are present in the steady noncycling storms.

Figures 21 and 22 do not include several of our additional findings, however. We demonstrated that extremes of shear confined to either the lowest or highest altitudes tended to slow down cycling, except when storms transitioned to NOCM. Assuming that the measure of shear in the diagram contains an average value through the troposphere, the schematic then remains approximately correct. In cases in which both OCM and NOCM were simulated, confining the low-level hodograph curvature (and majority of the helicity) to a shallower depth favored NOCM.

The NOCM simulations also demonstrated some trends that are not included in the schematic. Initial and subsequent mesocyclones appear to be delayed with increasing rectilinear shear, similar to OCM. At higher shears, there was some evidence that the NOCM cycles became shorter, a trend opposite to that observed in OCM.

Although a detailed assessment of the physical mechanisms associated with cycling variability is beyond the scope of this paper, we can make several general observations. For very weak environmental shear, updraft rotation throughout the depth of the storm is minimal and the near-ground mesocyclone never intensifies. No rear-flank downdraft (RFD) surge or gust-front bowing is evident, and the gust front and near-
ground mesocyclone remain in a quasi-steady configuration, that is, a steady noncycling storm. At higher shears, near-ground mesocyclogenesis is much stronger, and a progression of the occlusion cycle as in AD99 occurs, that is, an OCM storm.

When the shear is increased beyond some critical value, the gust front assumes a quasi-steady configuration, accompanied by a strong near-ground mesocyclone and large inflow winds. Although the exact physical mechanism that allows such a balance is not clear, RFD surges are not accompanied by large displacements in the gust front and the occlusion process does not begin, again resulting in a steady noncycling storm. However, for cases in which surface winds in the RFD and storm outflow become nearly parallel to the north–south-oriented gust front, the near-ground mesocyclone tends to propagate southward, eventually decoupling from the main updraft and resulting in a NOCM storm. Again, it is not obvious what physical mechanism allows for this behavior.

A natural question to ask is whether the timing of the occlusion cycles (for the OCM storms) can be correlated with any of the indices that characterize the initial environmental sounding. Scatterplots of the time of the first mesocyclone occlusion versus BRN6, BRN9, SRH1, SRH3, and storm-relative surface inflow (SRIN) (not shown) demonstrate that no index is clearly superior in discriminating among occlusion timings (Adlerman 2003). Plotting the same timings as a function of two sounding indices (e.g., contouring the time of first occlusion on a plot of BRN versus SRH) is of little additional value as BRN and SRH are not really independent of one another in our soundings.

A more significant difference in indices is found between our OCM and NOCM cases. Figures 23a and 23b display a comparison of box and whisker plots of SRH1, SRH3, BRN6, BRN9, and SRIN for the OCM, NOCM, and steady simulations. It is clearly evident from these that NOCM tends to dominate when the initial sounding has a higher SRH, lower BRN, and a larger storm-relative inflow.

The ability to predict the mode and periodicity of storm cycling a priori remains a difficult problem. Our results suggest that some general inferences can be made based upon hodograph shape and an average magnitude of the vertical shear, but that standard indices such as SRH or BRN do not contain much predictive value. However, for discriminating only between OCM versus NOCM, a stronger signal was apparent. That is, we showed that NOCM tends to dominate
Fig. 23. (a) Box and whiskers plots of 0–6-km BRN, 0–9-km BRN, and storm-relative surface inflow for the OCM, NOCM, and steady simulations. Mean value indicated by the triangle. Outliers indicated by the hollow circles. (b) As in (a), except for 0–1-km SRH and 0–3-km SRH.
when the initial sounding has a higher SRH, lower BRN, and a larger storm-relative inflow.

Before any operational prediction of cycling characteristics can be made, much more work needs to be performed in several areas. First, a complete exploration of the influence of the temperature and moisture profiles upon cycling should be performed, similar to the work of McCaul and Cohen (2000, 2002) and McCaul and Weisman (2001). In addition, the impact of ice physics needs to be addressed. These are not trivial tasks, as ideally one would like to repeat the thermodynamic alterations for most of the hodograph variations. This would result in several hundred simulations, each of which must be subjectively analyzed.

Finally, a comparison of the numerical simulations with radar observations is necessary to understand the prevalence of each type of cycling mode and whether the simulated storms correctly correspond with the observed environmental conditions. Because some of the most easily distinguishable characteristics of OCM versus NOCM occur near the surface, the classification process may be rather difficult unless the storm is within close range of current fixed radars. This comparison also would need to address the level of complexity required in the simulations to be comparable with observed modes of cycling. The role of surface friction, realistic initialization techniques, and more sophisticated microphysics would inevitably be important for assessing the predictability of cyclic modes and timings.

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