The Sensitivity of Numerically Simulated Cyclic Mesocyclogenesis to Variations in Model Physical and Computational Parameters

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ABSTRACT

In a previous paper, a three-dimensional numerical model was used to study the evolution of successive mesocyclones produced by a single supercell storm, that is, cyclic mesocyclogenesis. Not all supercells, simulated or observed, exhibit this behavior, and few previous papers in the literature mention it. As a first step toward identifying and understanding the conditions needed to produce cyclic redevelopments within supercell updrafts, this paper examines the effect on cyclic mesocyclogenesis of variations in model physical and computational parameters. Specified changes in grid spacing, numerical diffusion, microphysics options, and the coefficient of surface friction are found to alter, in some cases dramatically, the number and duration of simulated mesocyclone cycles.

For example, a decrease from 2.0 to 0.5 km in horizontal grid spacing transforms a nearly perfectly steady, noncycling supercell into one that exhibits three distinct mesocyclone cycles during the same time period. Decreasing the minimum vertical grid spacing at the ground tends to speed up the cycling process, while increasing it has the opposite effect. Ice microphysics is shown to cut short the initial cycling, while both simple surface friction and increased numerical diffusion tend to slow it down. Combining competing effects (i.e., ice microphysics with friction) tends to bring the simulation back to the evolution found in the control case. Explanations for these results are offered in the context of nonlinear feedbacks associated with the cycling process. In addition, the implications of these findings in our understanding of storm behavior as well as in the context of storm-scale numerical weather prediction are discussed.

1. Introduction

In recent years, significant progress has been made in our understanding of both midlevel and near-ground mesocyclogenesis within supercell thunderstorms (e.g., see the review by Davies-Jones et al. 2001). Numerical simulations have investigated the effects of low-level thermal boundaries upon mesocyclogenesis (e.g., Atkins et al. 1999), and have progressed further downscale to the point where tornadogenesis may be captured in the context of an entire supercell storm (Grasso and Cotton 1995; Wicker and Wilhelmson 1995).

An interesting aspect of mesocyclogenesis is the propensity for successive redevelopment within the same storm (i.e., "cyclic mesocyclogenesis"; Burgess et al. 1982). Adlerman et al. (1999) studied this phenomenon via the numerical simulation of a classic supercell storm and showed that, over a 4-h period, the modeled mesocyclone underwent two distinct occlusions separated by an interval of approximately 3600 s. This behavior was shown to be consistent with conceptual models proposed by Lemon and Doswell (1979) and Burgess et al. (1982).

Early observational studies (Darkow and Roos 1970; Burgess et al. 1982) suggested that the cyclic mesocyclone occlusion process could have a wide range of timescales (i.e., cyclic does not necessarily imply periodic), varying between 1200 and 7200 s. A recent observational study by Dowell and Bluestein (2002a,b) suggested that, even within a single storm, the cyclic process may undergo large variations in timing and character. Although Dowell and Bluestein proposed a characterization of cyclic behavior based upon the ratio of inflow and outflow strength, the physical processes governing cycling, and the factors delineating a cyclic from a noncyclic storm, remain poorly understood.

Numerical simulation models have proven extremely valuable in the study of deep convective storms and have provided insight into the dynamics of even intricate processes like cyclic mesocyclogenesis. However, such
models are known to exhibit sensitivities arising from their formulation, numerical architecture, parameter settings, and initial and boundary conditions (e.g., Klemp et al. 1981; McPherson and Droegemeier 1991; Brooks 1992; Droegemeier and Levit 1993; Weisman et al. 1997; Richardson 1999). Although such sensitivities are well known, their behavior and impact have been examined largely within the context of studies having broader goals. For example, most investigations of deep convective storms, such as those involving subsets of large parameter spaces for which computational costs can be significant (e.g., Weisman and Klemp 1982, 1984), have reported that model solutions are “qualitatively the same” (Weisman and Klemp 1982, p. 506) if, for example, the grid spacing is doubled or halved. Similarly, a comprehensive set of sensitivity tests conducted for a single simulation of an observed tornadoic storm by Klemp et al. (1981) showed that “the basic evolution and structure of the storm [were] not substantially affected by these changes” (Klemp et al. 1981, p. 1578).

With the intent of determining the grid spacing necessary to avoid the use of a convective parameterization scheme within a mesoscale model, Weisman et al. (1997) investigated resolution sensitivity as applied to squall-line simulations. They showed that, even with horizontal grid spacings ranging from 1 to 12 km, many aspects of the simulated convective system (e.g., overall circulation structure and transports) were represented with a reasonable degree of fidelity. The greatest impacts of resolution change were manifest in system timescale, rainfall rates, intensity, and size.

Reductions in grid spacing appear to be least important when a particular numerical solution is grid-converged, that is, when “no meaningful improvement in a numerical solution [can] be obtained using higher resolution within the practical limits of finite precision, speed, and memory of a computing machine” (Straka et al. 1993b, p. 2). Grid convergence can usually be determined by using Richardson extrapolation (Richardson 1910, 1927) to estimate the error in a fine versus coarse grid comparison. A standard grid convergence index (GCI) can then be computed, as described by Roache (1998). By comparing simulations of a nonlinear density current with a grid-converged reference solution, Straka et al. (1993b) demonstrated that various numerical techniques will perform similarly for a well-resolved flow, but that solutions begin to diverge as the flow becomes more marginally resolved (see also Droegemeier et al. 1994).

Fovell (1996) investigated the effects of background numerical diffusion (i.e., “computational mixing”) on the structure of both two- and three-dimensional numerically simulated squall lines. In contrast to the previously discussed sensitivity studies, he noted that the widths of both the transient and forced updrafts could be modified by varying solely the background numerical diffusion. Although all of the simulations remained dynamically similar, this is nonetheless a surprising result, as background diffusion is generally hoped to have little impact upon the physically relevant parts of the solution. However, Lilly and Jewett (1990) did note that background diffusion could dominate physical turbulent mixing in some storm simulations.

In light of important and sometimes contradictory model sensitivities like those described above, and as the first step toward a broader goal of identifying and understanding the conditions needed to produce cyclic redevelopments within supercell updrafts, we examine the effect on cyclic mesocyclogenesis of variations in model physical and computational parameters. In particular, we consider the horizontal and vertical grid spacing, along with the coefficient of surface friction, microphysics options, and the coefficient of numerical diffusion (see Fig. 2). These specific parameters are evaluated because their specification usually is left to the discretion of the model user, and because they can have a significant impact on the character of the numerical solution, especially for storm-scale flows.

The results presented herein, like those of Fovell (1996), show that model configuration and, in particular, grid spacing are critically important in controlling some aspects of simulated storm morphology. For example, a decrease from 2.0 to 0.5 km in horizontal grid spacing transforms a nearly perfectly steady, noncycling supercell into one that exhibits three distinct mesocyclone cycles during the same time period. This result is not entirely unexpected, as a grid spacing of 2 km results in a mesocyclone that is represented by only three or four gridpoints. However, such issues must be considered for both storm-scale numerical weather prediction (NWP) (Lilly 1990; Droegemeier 1997), where the practicable near-term operational grid spacings appear to be of order 1–10 km, as well as for the use of numerical models in studying the dynamics of deep convective storms. In fact, we postulate that previous modeling studies have sometimes failed to recognize cyclic behavior because of this sensitivity to grid spacing, in addition to the numerous others sensitivities described herein. However, we must also note that cyclic mesocyclogenesis may not be observed if the duration of the simulation is sufficiently limited (i.e., of order 7200 s).

It is important to note that some of the changes in storm morphology exhibited here are in reference to small-scale features and behaviors. Indeed, it can be argued that some characteristics of the simulated storms actually are quite consistent among experiments given the parameter changes imposed. For example, none of the variations shift the mode of convection away from the supercell regime, and most of the timing variations are on the order of minutes (small in comparison to storm lifetime). However, because we are considering the implications of our results in the context of storm-scale numerical prediction, where the predictive window may be less than an hour to a few hours in length, such
seemingly minor details (e.g., storm motion or cyclic regeneration) may in fact be extremely important.

Owing to the large number of experiments that could be performed in this type of parameter study, the present experiments necessarily are limited in scope. We believe they do, however, encompass an important range of behavior relevant to many contemporary cloud-scale simulation studies. Although our findings raise interesting and perhaps disturbing questions regarding model sensitivity, they should not be viewed as invalidating previous results. Rather, they are meant to serve as a basis for understanding physically some of the inevitable consequences associated with using numerical models. Further, for the reasons noted above, the results presented herein are not intended to serve as a guide for operational prediction, or for the choice of parameters in other cloud-scale models, where differences in model formulation alone are known to impact solution reproducibility (Richardson 1999).

This paper is organized as follows. Section 2 discusses the numerical model as well as the experimental setup, and section 3 describes the control run. Section 4 discusses the sensitivities to computational parameters while section 5 details the sensitivities to physical parameters. Finally, we summarize in section 6 the results and discuss their implications.

### 2. Experiment design

The simulations described in this study are made using version 4.4 of the Advanced Regional Prediction System (ARPS), a three-dimensional, compressible, nonhydrostatic model developed for storm-scale numerical weather prediction (Xue et al. 1995, 2000, 2001, 2002). The model setup for the control run is nearly identical to that described in Adlerman et al. (1999) and is shown in Table 1. The computational grid has uniform horizontal spacing of 0.5 km within a 90 km × 90 km × 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 via

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

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

Here, \(\Delta z_{av}\) is the average grid spacing (0.4 km), \(nz\) is the number of grid points in the vertical (43), \(\alpha\) is a tuning parameter set to unity, and \(a = [1 + (nz - 3)/2]\). Cloud microphysics is represented using the Kessler (1969) warm-rain parameterization, and neither the Coriolis force nor the surface physics package is used.

Differences in experiment configuration from those used in Adlerman et al. (1999) include (owing to the availability of a new model version) the use of a higher-order (4th versus 2nd) advection scheme for all quantities, along with several small corrections to the implementation of the 1.5-order subgrid-scale turbulence scheme. These changes produce a new control simulation (see section 3) that is extremely similar, though not perfectly identical, to the experiment reported in Adlerman et al. (1999). Because the cycling process of the new control run is dynamically the same as in Adlerman et al. (1999), any differences between the two are deemed irrelevant because all comparisons here are made relative to the former.

In all simulations, the horizontally homogeneous model base state is initialized using a composited sounding associated with the 20 May 1977 Del City, Oklahoma, storm (Ray et al. 1981; Klemp et al. 1981; Johnson et al. 1987). A mean storm motion \((u, v) = (3, 14) \text{ m s}^{-1}\) is subtracted from the sounding to keep the storm as far away as possible from the lateral bound-

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### Table 1. Physical and computational parameters used in the control simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Horizontal resolution</td>
<td>(\Delta x, \Delta y)</td>
<td>500 m</td>
</tr>
<tr>
<td>Vertical resolution</td>
<td>(\Delta z)</td>
<td>100 m ≤ (\Delta z) ≤ 700 m</td>
</tr>
<tr>
<td>Large time step</td>
<td>(\Delta t)</td>
<td>3.00 s</td>
</tr>
<tr>
<td>Small time step</td>
<td>(\Delta r)</td>
<td>0.5 s</td>
</tr>
<tr>
<td>Coriolis parameter</td>
<td>(f)</td>
<td>0.0 s(^{-1})</td>
</tr>
<tr>
<td>Nondimensional surface drag coefficient</td>
<td>(C_d)</td>
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</tr>
<tr>
<td>Fourth-order horizontal mixing coefficient</td>
<td>(K_i)</td>
<td>(6.25 \times 10^3 \text{ m}^4 \text{ s}^{-1})</td>
</tr>
<tr>
<td>Second-order vertical mixing coefficient</td>
<td>(K_z)</td>
<td>(1.5 \leq K_z \leq 73.5 \text{ m}^2 \text{ s}^{-1})</td>
</tr>
<tr>
<td>Divergence damping coefficient</td>
<td>(\alpha)</td>
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</tr>
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<td>Initial thermal perturbation</td>
<td>(\Delta \theta)</td>
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</tr>
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<td>Horizontal radius</td>
<td>(x, y)</td>
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</tr>
<tr>
<td>Vertical radius</td>
<td>(z)</td>
<td>1.5 km</td>
</tr>
<tr>
<td>Height of center above ground</td>
<td>(z_c)</td>
<td>1.5 km</td>
</tr>
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<td>Microphysics</td>
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<td>Kessler warm rain parameterization</td>
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<td>Lateral boundary conditions</td>
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<td>Radiation</td>
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<tr>
<td>Top boundary conditions</td>
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<td>Rigid with Rayleigh sponge layer</td>
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<td>Grid stretching function</td>
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<td>Hyperbolic tangent</td>
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<tr>
<td>Horizontal and vertical advection</td>
<td></td>
<td>Fourth order</td>
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<tr>
<td>Turbulence parameterization</td>
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<td>Anisotropic 1.5-order TKE closure</td>
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</tbody>
</table>
aries. The model is integrated for 14 400 s, and history files are saved every 500 s starting at 1800 s. As in Adlerman et al. (1999), the goal of these experiments is not to replicate the actual thunderstorms of 20 May 1977, but rather to examine sensitivities associated with an idealized numerical simulation based upon the associated observed sounding. An event with more complete observational data, such as that studied by Dowell and Bluestein (2002a,b), would be more amenable to a case study approach.

3. Control simulation

As in Adlerman et al. (1999), the principal storm in the control simulation (hereafter denoted the control storm) develops into a mature supercell by 3600 s, with a pronounced hook echo and strong mesocyclone [defined by Doswell and Burgess (1993) as a 3–9-km-diameter region of vertical vorticity $> 0.01 \text{ s}^{-1}$ with both height and time continuity] evident by 5400 s. The mesocyclone occlusion process begins after 6000 s (Fig. 1) with the development at 4-km altitude of a two-celled updraft structure and an occluded surface gust front. Surface vorticity peaks at 7500 s, after which the original (first) mesocyclone decays and a new one develops rapidly to its east.

Also as in Adlerman et al. (1999), a dual-hook structure is evident in the rainwater field at 4-km altitude during the transition from the first to second mesocyclone cycle (see Figs. 20 and 22 in that paper). Although this transition occurs approximately 500 s later in the present simulation, it also proceeds in a more continuous and rapid manner than in Adlerman et al. (1999), as evidenced by the close proximity of the old and new surface mesocyclones (Fig. 1) and a more rapid progression to an occluded gust front structure by 9300 s (cf. with Figs. 20, 22, 23, and 25 of Adlerman et al. 1999).

The second mesocyclone cycle proceeds similarly to the first, with a second occlusion occurring at approximately 11 400 s, or some 500 s later than in Adlerman et al. (1999). The storm evolution after 13 000 s is slightly different, as the third cycle in the present run continues without another occlusion until the end of the simulation at 14 400 s. This may be attributed to the development of other convection within the domain, which begins to interact with the principal storm of interest toward the end of the run. The secondary convection is greatly reduced, but not eliminated, when a more strongly damped second-order advection scheme is used, as in Adlerman et al. (1999). As a result of this intervening convection, we confine our comparisons against the control run to the period prior to 12 600 s.

4. Sensitivity to computational parameters

a. Numerical diffusion

Background diffusion is added to a numerical model to reduce spurious oscillations that result from truncation error (numerical dispersion), nonlinear instability (aliasing), and the discontinuous representation of physical processes (e.g., condensation). These diffusion terms act as explicit artificial viscosity (in addition to explicit subgrid-scale physical turbulent mixing), damping perturbations back to the base state. Because numerical diffusion damps most strongly those waves having a wavelength of two grid intervals (referred to here as $2\Delta x$, irrespective of coordinate direction), solutions using different magnitudes of artificial viscosity should remain qualitatively similar as long as the damping coefficients are specified to be sufficiently small.

In order to examine the effects of numerical diffusion on mesocyclone cycling, we repeat the control run with the numerical diffusion both halved and doubled. Figure 2 shows the variations in the length and timing of each cycle during the period 5400–12 600 s. Each distinct cycle is indicated by a separate horizontal bar, shaded accordingly. In the case of doubled numerical diffusion, storm evolution slows dramatically and becomes much more steady (Fig. 2). Indeed, the effect of this parameter change is very similar to that associated with the coarser grid spacing (>1 km) runs (section 4b). The transition between the first and second cycles does not occur until nearly 12 300 s, which is approximately 4500 s slower than in the control run. A third cycle (not shown) is indicated at the end of the run, or 3000 s later than in the control case.

Although a substantial amount of noise is introduced into the solution when background diffusion is halved, early storm evolution remains quite similar to the control run. The first mesocyclone occlusion occurs near the same time (Fig. 2), while the second occurs approximately 300 s earlier. Because the “optimal” amount of computational smoothing should suppress noise while having minimal impact on the physically important scales of the solution, this suggests a posteriori that the values used in our control run are appropriate for the chosen grid spacing.

The underlying cause of the solution changes noted above must be the diffusion of gradients, which is the net effect of computational mixing. However, the excess diffusion does not merely prolong the length of the first cycle, but actually modifies the transition between cycles. This is illustrated in Fig. 3, which shows time–height plots from 3600 to 12 600 s of maximum vertical vorticity for the control run and the doubled numerical diffusion run. A similar pattern is evident, with two distinct maxima separated by a minimum. In the control run, the minimum at 8600 s represents the reorganizing stage between the first and second mesocyclone cycles, when the dual-maxima updraft–mesocyclone structure separate and the old updraft decays as the new one intensifies (Adlerman et al. 1999). However, in the doubled-mixing run, the minimum at 8600 s (Fig. 3) represents a transition, where the dual-maxima updraft–mesocyclone actually merges back together after separating (Fig. 4). Instead of an occlusion occurring at the surface, the near-ground...
FIG. 1. (a) Horizontal cross section of vertical velocity at (left) $z = 0.05$ km and (right) $z = 4$ km at $t = 6000$ s for the control run. Isoline of 1 g kg$^{-1}$ rainwater-mixing ratio is indicated by the single dark contour. Grid-relative wind vectors are indicated. Contour interval of vertical velocity is (left) 0.2 m s$^{-1}$ and (right) 2.5 m s$^{-1}$. (b) Same as in (a) except for $t = 7800$ s. (c) Same as in (a) except for $t = 8400$ s. Throughout, the first mesocyclone location is indicated by a heavy dashed line and the second mesocyclone location is indicated by a lighter dashed line.
mesocyclone temporarily weakens before the occlusion process resumes at 9600 s.

The cause of this temporary reversal in the occlusion process appears to be the inability of the near-ground mesocyclone to intensify sufficiently to allow the occlusion process to continue. Although the magnitudes of updrafts, downdrafts, and surface winds are quite similar in these two simulations, the quantities found most important for near-ground mesocyclogenesis in the previous analysis of this simulation by Adlerman et al. (1999) are not: streamwise vorticity stretching (as illustrated by the Boussinesq horizontal vorticity equation in seminatural coordinates) and vertical stretching. The maximum streamwise stretching and vertical convergence just prior to the reversal of the occlusion process are reduced by approximately 75% compared to those in the control run. This appears to result from weaker horizontal convergence (reduced by 33%) and horizontal vorticity (reduced by 25%), which are decreased at least in part by the excessive smoothing of velocity gradients. Therefore, although the numerical solution may not appear to be excessively damped, increased numerical diffusion easily disrupts the cycling process.

b. Grid spacing

Computational resources constrain the grid spacing and domain size that can be used in limited area numerical simulations. Ideally, spacings that ensure a grid-converged solution should be used, but this concept is vague when applied to complex multiphase flows. Early numerical simulations for the purpose of classification yielded storm evolutions that were “qualitatively the same” (Weisman and Klemp 1982, p. 506) when the horizontal spacing was varied between 1 and 2 km. Although this might be considered grid-converged for the purpose of understanding basic storm morphology (e.g., supercell versus multicell), it may be inadequate when considering other characteristics, such as precipitation amount, which Weisman et al. (1997) have shown is notably sensitive to grid spacing.

Kolmogorov scaling shows that the smallest scales of turbulence, at which energy is dissipated, are on the order of millimeters for high Reynolds number flows (e.g., Garratt 1994). The turbulence closure scheme used in most numerical simulations calculates the coefficients of physical mixing based on the grid scale. Because storm-scale simulations always use grid spacings much larger than the Kolmogorov length scale, gradients will always tend to collapse to the smallest resolvable scale, $\Delta x$.

From a scaling viewpoint, maximum values of vorticity should at least double every time the grid spacing is halved, increasing without bound as long as the grid spacing remains larger than the Kolmogorov length scale. The increase most likely will be larger in practice, however, as values of velocity also will increase as the energetic small scales are explicitly captured rather than relegated to the subgrid-scale turbulence. Droegemeier et al. (1994) demonstrated that this indeed occurs, with maximum vertical vorticity increasing from 4 to $88 \times 10^{-2}$ s$^{-1}$ when the horizontal grid spacing was decreased from 2 to 0.25 km in a supercell simulation. They also showed that maximum updraft speed increased from 27 to 64 m s$^{-1}$ over the same range, approaching the theoretical value of 68 m s$^{-1}$ predicted by the CAPE. The solution change was highly nonlinear, however. For example, as the grid spacing was incrementally halved from 2 to 0.25 km, the average updraft speeds computed over the first 25 min of development were 23, 28, 41, and 46 m s$^{-1}$, respectively.

The determination of adequate grid spacing is inevitably tied to the degree to which the representation of small scales alters the evolution of larger scales, and vice versa. It is usually assumed that the impact of minor alterations in grid spacing will be minimal. However, in the context of mesocyclone cycling, we show below that small (factor of 2) changes in grid spacing can have a significant impact upon the solution.

1) Horizontal grid spacing

In order to examine the effects on mesocyclone cycling of horizontal grid spacing, the 0.5-km grid spacing control run is repeated using spacings of 1, 1.5, and 2
FIG. 3. Time-height cross section of vertical-vorticity maxima (10^{-3} s^{-1}) for (left) the control run and (right) the doubled numerical diffusion run. Maxima were calculated from unsmoothed 5-min data only in the relevant area of the domain, i.e., that subsection that encompasses the entire storm of interest.
km. These results also are compared to a simulation conducted using a horizontal grid spacing of 105 m (Adlerman and Droegemeier 2000), which utilized the two-way interactive nested grid capability of ARPS.

At 1-km spacing (twice as coarse as the control run), the timing of the cycling (as determined by the time at which the surface mesocyclone and associated updraft completely occlude) slows down slightly with respect to the control run (Fig. 2). The beginning of the second cycle is delayed by approximately 300 s, while the transition to the third cycle is delayed by approximately 600 s. The entire length of the second cycle is about 300 s longer. Other than these timing differences, storm evolution is in all respects qualitatively similar to the control run.

At 1.5- and 2-km grid spacings, a dramatic transition occurs and the cyclic behavior of the storm ceases entirely (Fig. 2). In fact, at 2-km spacing, the storm remains essentially steady even when the simulation is extended to 21,600 s (Fig. 5). At 1.5-km grid spacing, there is some indication that the modeled storm attempts to cycle, as evidenced by the appearance of a transient dual-maxima updraft–mesocyclone structure above 2 km (not shown). However, the 2-km run shows no such behavior, and is entirely unicellular throughout its lifetime. This transition from cyclic to noncyclic behavior clearly is evident in the trends of maximum vertical vorticity below 2 km (Fig. 6).

Several additional experiments were undertaken to examine solution behavior at coarse grid spacings. In order to confirm that the cycling has not slowed to an interval greater than 21,600 s, the coarse grid runs (1.5- and 2-km grid spacings) were extended to 28,800 s, again resulting in an almost purely steady-state, non-cycling supercell. The addition of ice physics (section 5) at 2-km grid spacing causes the updraft and gust front to exhibit greater variations in shape and orientation than in the warm rain simulation, yet the storm remains essentially steady for 28,800 s and does not cycle. If numerical diffusion in the 2-km grid spacing run is reduced to a level where noise is introduced (1/4 of the original value), slightly more unsteady behavior is observed. It appears that the storm attempts to cycle after 18,000 s, although the transition remains poorly resolved.

The change in grid spacing not only has an apparently abrupt effect on the character of the cycling, but also strongly affects the translational motion of the surface mesocyclones. Figure 7 displays plots of the maxima in vorticity (approximately the center of the surface mesocyclone) at \( z = 50 \) m (lowest horizontal velocity level).
Fig. 5. (a) Horizontal cross section of vertical velocity and rainwater-mixing ratio at (left) \( z = 0.05 \) km and (right) \( z = 4.0 \) km at \( t = 7200 \) s for the 2-km grid spacing run. Vertical velocity contour interval is (left) 0.1 m s\(^{-1}\) and (right) 3 m s\(^{-1}\). Isoline of 1 g kg\(^{-1}\) rainwater-mixing ratio is indicated by the single dark contour. (b) Same as in (a) except at \( t = 14400 \) s. (c) Same as in (a) except at \( t = 21600 \) s.
associated with the 0.5-, 1-, and 2-km grid spacing runs (the storm motions are “compressed” in space as a mean wind has been subtracted from the initial sounding). Note the sharp transition in motion from the cycling to noncycling simulations, in addition to the deviations between the cycling cases. Depending on grid spacing, the location of the storm’s mesocyclone toward the end of the simulation (12 600 s) varies by as much as 18 km. In terms of small-scale predictability and future storm-scale NWP, this may be a significant difference.

Time-averaged values of domain-wide maximum vertical vorticity, computed over the length of each simulation from 60-s data, scale at the expected rate, approximately doubling each time the grid spacing is halved (Fig. 6). Domain-wide maximum instantaneous values of vertical vorticity (Fig. 6) scale more nonlinearly with grid spacing, similar to the trend found in Droegemeier et al. (1994). These increases become larger with smaller grid spacing, suggesting that the vorticity does not converge as finer scales of motion are explicitly represented.

Values of domain-wide maximum updraft (Fig. 8) increase more slowly as grid spacing is decreased. From 2 to 1 km, the average maximum increases by 25%, while from 1 to 0.5 km, the increase is 12%, suggesting that the numerical solution is beginning to converge.

When the 20 May 1977 sounding is interpolated to the model grid, it yields a CAPE of 2324 J kg$^{-1}$, calculated using the virtual temperature correction (Doswell and Rasmussen 1994), neglecting ice processes (Williams and Renno 1993), and taking into account water loading. Neglecting the important contribution of nonhydrostatic vertical pressure gradients in an environment with a strongly curved hodograph (Weisman and Klemp 1984; McCaul 1991; Brooks and Wilhelmson 1993; McCaul and Weisman 1996), entrainment (e.g., Cohen 2000), and the strong influence of vertical variations in the distribution of buoyancy and shear (McCaul and Cohen 2000; McCaul and Weisman 2001), this CAPE yields a theoretical maximum updraft speed of approximately 68 m s$^{-1}$, indicated in Fig. 8 by the single horizontal dark line. Although a grid-converged solution might not always be expected to contain vertical velocities that approach parcel theory values, the Del City sounding is consistent with those that tend to approach full realization of CAPE-based updraft potential (Cohen 2000; McCaul and Cohen 2000; McCaul and Weisman 2001). Instantaneous maximum values of vertical velocity (Fig. 8) appear to be slowly approaching the parcel theory value, with the 0.5-km simulation containing a peak updraft of 61.5 m s$^{-1}$.
In order to determine whether the control run is grid-converged, a nested-grid simulation (Adlerman and Droegemeier 2000) at a grid spacing of 105 m is used for comparison. Cyclic mesocyclogenesis proceeds more rapidly at this finer spacing, with the transitions between the first and second (second and third) cycles accelerated by 600 (900) s. The maximum instantaneous value of vertical velocity has increased to 66 m s\(^{-1}\). Although this value is approaching that of parcel theory, the timing differences are comparable to those between the 0.5- and 1-km simulations, so it remains unknown whether a 105-m grid spacing yields a converged solution.

Based upon the transition from cycling to noncycling behavior in these horizontal grid spacing experiments, it is clear that the process of cyclic mesocyclogenesis cannot be resolved on a 2-km grid for this particular set of environmental conditions. In order to determine whether the results from the 2-km simulation could be replicated by sampling—at the same spacing—results from a higher-resolution run, variables from the 1-km simulation are quadratically interpolated to a 2-km grid every 300 s (i.e., for each history data file). When the interpolated variables are animated in time, the cyclic evolution remains evident. However, if the variables are interpolated onto a coarser grid (e.g., 4 km) the storm visually is steady. Therefore, it appears that the inability to resolve cycling on the 2-km grid is not entirely an issue of sampling.

Because finer-scale features will be better represented with smaller grid spacings, the resolved percentage of kinetic energy within the simulation should increase as the grid spacing is reduced. An asymptotic value near 100% should be approached as most of the energetic motions are resolved on the grid scale and the subgrid-scale turbulent kinetic energy (TKE) approaches zero. The percentage of resolved kinetic energy was calculated for each history file of the variable grid spacing simulations by averaging over horizontal slices of the entire domain in regions where the subgrid-scale turbulence was active. Surprisingly, the 2-km run has the highest overall percentages of resolved kinetic energy throughout the simulation, with values usually varying between 98% and 99% (Fig. 9a). As the horizontal grid spacing is decreased toward that of the control run, these percentages decrease slightly at all levels except the lowest few grid points (Figs. 9b,c). For comparison, the resolved percentage of kinetic energy was also calculated for the 105-m horizontal grid spacing nested-grid
simulation. Near the ground, where the grid spacing is nearly isotropic, the percentage of resolved kinetic energy has increased to greater than 99% throughout the simulation (Fig. 9d). At upper levels, where the vertical grid spacing is significantly larger owing to stretching, the resolved percentages drop to below 90%. Since the 105-m simulation is on a nested grid, it is important to note that the region in which these percentages are calculated will be artificially smaller than a similar non-nested simulation. However, since the minima in Fig. 9d correlate well with the simulated storm’s updraft pulses (and associated stronger gradients), it appears that these data are still representative of this simulation.

These results suggest that in the 2-km simulation, the storm is so poorly resolved that the subgrid-scale turbulence scheme seriously underpredicts the amount of energy that should be present. As the resolution improves and gradients of all variables increase, the subgrid-scale scheme predicts a proportionally larger amount of subgrid-scale energy. Only when the grid spacing decreases to a nearly isotropic value of 100 m does the resolved percentage of kinetic energy correctly approach 100%, as most of the significant eddies are represented on the grid scale.

An analysis of the transition between the noncycling (2 km) and cycling (1 km) runs shows only minor differences in the magnitude of updrafts, downdrafts, and mass fluxes. However, the maximum magnitude of the surface buoyancy gradients (northwest of the near-ground mesocyclone) and surface horizontal convergence (along the gust front) are reduced by 45% and 38%, respectively, in the 2-km run. Vertical vorticity approximately scales as would be expected (see above) when the horizontal grid spacing is increased to 2 km, with values at both upper and lower levels that are considered marginally representative of mesocyclone strength, that is, approximately 0.01 s$^{-2}$. The reduction in surface horizontal gradients and vertical vorticities results in a 70% decrease in the maximum vertical vorticity convergence in the near-ground mesocyclone, and a 45% reduction in the maximum streamwise stretching. The lack of any strong vortex stretching keeps the near-ground mesocyclone from intensifying and prevents the rear-flank downdraft (RFD) from moving the gust front eastward. Consequently, the occlusion cycle is never able to reach the critical point at which feedback processes (Adlerman et al. 1999) allow it to continue. Although discrete updraft–downdraft pulses still are present in the 2-km simulation, along with their resultant effect on variations in vorticity and pressure perturbations, the storm still appears to be nearly steady state. However, it would be misleading to characterize its dynamics as representative of a steady-

![Figure 8](image)

**Fig. 8.** Values of domain-wide maximum vertical velocity (m s$^{-1}$) vs time (s) for each of the horizontal grid-spacing experiments. The CAPE-based updraft maxima of 68 m s$^{-1}$ is indicated by the single black line. Data were taken at 60-s intervals.
state supercell, as its behavior appears to result from inadequately resolved processes.

2) VERTICAL GRID SPACING

The control run utilized a minimum vertical grid spacing \( (\Delta z_{\text{min}}) \) at the ground of 100 m that increased smoothly to 700 m at the top of the domain, according to Eq. (1). In order to explore the effects of varying the vertical grid spacing, the control run is repeated with \( \Delta z_{\text{min}} \) increased to 200 m and decreased to 50 m. The stretching function is not altered in these runs, and therefore the grid spacing changes throughout the depth of the entire domain. However, because the stretching function is proportional to the hyperbolic tangent of the vertical grid index, the finest grid spacing remains concentrated at the lowest levels. With these parameters, the number of grid points below 2 km is (10, 15, 18) for \( \Delta z_{\text{min}} = (200, 100, 50) \) m.

When the minimum vertical grid spacing is lowered
to 50 m, mesocyclone cycling is accelerated slightly (Fig. 2). The transition between the first and second cycles occurs about 300 s earlier than in the control run, and the length of the second cycle is 600 s shorter. Subsequently, the transition between the second and third cycles occurs 900 s earlier than the control run. When the minimum vertical grid spacing is increased to 200 m, the opposite occurs and cycling slows significantly (Fig. 2). The transition between the first and second cycles occurs 2700 s later than in the control run. A transition to a third cycle is indicated near the end of the run at 14 100 s (not shown), approximately 2700 s slower than in the control run.

In contrast to the horizontal grid spacing experiments, storm morphology in the vertical grid spacing experiments is qualitatively similar. Maximum updraft and downdraft speeds remain within ±5% of one another, and the relative positions of the gust front and surface cold pool also are very similar. When Δz_{min} = 50 m, the occlusion process appears to proceed nearly identically to that in the control run, with the cycles slightly compressed in time. When Δz_{min} = 200 m, the occlusion process also proceeds similarly, except that once the near-ground mesocyclone starts to occlude and the gust front is pushed far to the east, the cycle begins to slow down and remains quasi-steady (in this configuration) for approximately 1800 s. Once the near-ground mesocyclone finally becomes entirely cut off from the rest of the gust front, the occlusion process then proceeds as in the control run.

Because the vertical grid-spacing simulations are so similar, the exact cause for these timing differences is unclear. Changing the minimum vertical grid spacing near the ground does have a direct impact on maximum values of horizontal vorticity. As would be expected from scaling arguments, near-ground horizontal vorticity approximately doubles, relative to the control run, when Δz_{min} = 50 m, and decreases by half when Δz_{min} = 200 m. These variations appear only in the lowest 400 m of the domain and, thus, are located in a region where most of the vorticity dynamics associated with the occlusion process occur (Adlerman et al. 1999). Since much of the near-ground vorticity within these simulations originates from the transport and generation of horizontal vorticity (Adlerman et al. 1999), it appears reasonable that the ability to represent higher values of horizontal vorticity and to spin them up more quickly should accelerate the occlusion process, while the opposite effects should slow it down.

5. Sensitivity to model physics and physical parameters

a. Cloud microphysics

The inclusion of ice microphysics in a cloud model essentially adds an extra energy source/sink as a result of the additional latent heating of fusion. This usually strengthens both updrafts (e.g., Johnson et al. 1993; Straka and Anderson 1993; Straka et al. 1993a) and evaporatively driven downdrafts (e.g., Straka and Anderson 1993; Straka et al. 1993a), although downdraft weakening may occur in certain situations (Johnson et al. 1993). In addition to these effects, the redistribution of various hydrometeor types influences the characteristics of the surface cold pool, subsequently affecting the location and strength of surface convergence. The introduction of ice physics therefore can influence storm strength, type, and motion (Straka et al. 1993a).

In order to examine the effects of ice microphysics on mesocyclone cycling, the control run is repeated using a three-phase ice microphysics scheme (Lin et al. 1983; Tao and Simpson 1989). Storm evolution initially is accelerated quite significantly, with the cycling beginning earlier than in even the 105-m grid spacing run (Fig. 2). The transition between the first and second (second and third) cycles occurs 1200 (900) s earlier than in the control run. However, the duration of the second cycle lengthens to 3900 s, compared to 3600 s in the control run.

As expected, updrafts in the ice physics run are approximately 10% stronger than in the control run. Unlike some previous simulations (e.g., Straka et al. 1993a), maximum downdrafts are approximately the same strength, while maximum surface vorticity is 10% smaller than in the control run. However, a close inspection of time–height plots (not shown) reveals that the ice physics run contains evaporatively driven low-level downdrafts (<2.5 km above ground), which are up to 50% stronger than in the control run.

As air within these stronger downdrafts reaches the ground and spreads laterally, it tends to have a detrimental effect on the developing mesocyclone associated with the first cycle. Instead of allowing a gradual intensification of the surface mesocyclone as the gust front pushes outward and the RFD rotates around it, the near-ground mesocyclone appears to be sheared off from the gust front and pushed off toward the southwest, well before it can intensify (Fig. 10). Although the surface flow is slightly stronger in magnitude, this result may be due to the greater degree of parallelism between the surface outflow winds and the gust front (Fig. 10). It is not clear whether this results from a slightly different downdraft pattern, owing to the influence of ice microphysics, or whether the lack of a strong mesocyclone keeps the RFD from moving cyclonically around the northern part of the surface updraft. In either case, the effect of ice microphysics is to cut short the initial cycle of mesocyclogenesis, rather than accelerate the entire cycle.

b. Surface friction

Surface friction is included in the ARPS surface physics package, which includes parameterization of surface fluxes as momentum stresses at the lower boundary:
Fig. 10. Horizontal cross section of vertical velocity at the lowest grid point ($z = 50$ m) at (a) $t = 6000$ s, (b) $t = 6300$ s, and (c) $t = 6600$ s for the ice physics simulation. Contour interval is 0.2 m s$^{-1}$. Isoline of 1 g kg$^{-1}$ rainwater-mixing ratio is indicated by the single dark contour. Grid-relative wind vectors are indicated. The first mesocyclone location is indicated by a heavy dashed line and the second mesocyclone location is indicated by a lighter dashed line.

\[-\tau_{13}\text{surface} = \rho C_d [\bar{V}|\bar{u}| - |\bar{V}|\bar{u}] \quad \text{and} \quad (2)
\]

\[-\tau_{23}\text{surface} = \rho C_d [\bar{V}|\bar{v}| - |\bar{V}|\bar{v}], \quad (3)\]

where $\tau_{ij}$ is the momentum stress on a constant-$x$ plane in the vertical direction, $\tau_{33}$ is the momentum stress on a constant-$y$ plane in the vertical direction, $\rho$ is the air density, $C_d$ is a nondimensional drag coefficient, $|\bar{V}|$ is the wind speed, and overbars represent the base state. In this formulation, drag is applied only to perturbation velocities, as the base state is assumed to be in balance with friction (Wilhelmson and Chen 1982).

From basic principles, the introduction of surface friction into a horizontal flow over a flat surface creates a thin boundary layer in which momentum is reduced but with the larger-scale horizontal pressure gradient remaining nearly the same (Schlichting 1979). In terms of a storm-scale simulation, this tends to slow the motion of the cold pool and gust front (Mitchell and Hovemale 1977; Droegemeier 1985) and also increase radial convergence into areas of swirling flow at the ground (e.g., Wicker and Wilhelmson 1993).

Cyclic mesocyclogenesis in our runs was found to be extremely sensitive to the magnitude of the surface drag coefficient. For $C_d$ on the order of $10^{-2}$, the supercell storm dissipated prior to completing one mesocyclone cycle. This is somewhat surprising as such values usually are considered appropriate for convective modeling (e.g., Mitchell and Hovermale 1977; Wilhelmson and Chen 1982). However, similar sensitivity has been noted in other supercell storm simulations (e.g., Wicker and Wilhelmson 1995).

When the drag coefficient is reduced sufficiently to allow for a sustainable storm, surface friction has a direct impact upon the number and timing of the mesocyclone cycles. For $C_d = 10^{-3}$, the storm remains steady state for 14 400 s, with no cycling apparent (Fig. 2). Reducing $C_d$ to $5 \times 10^{-4}$ allows the storm to undergo one transition (two cycles). Compared to the control run, however, the second cycle is delayed by nearly an hour. Reducing the friction further to $C_d = 2.5 \times 10^{-4}$ decreases this delay to approximately 2100 s. A third cycling period was not observed in any of the friction runs.

The effect of surface friction upon the magnitude of the wind at the lowest grid levels appears to be relatively minor. Vertical cross sections taken through the surface cold pool (not shown) indicate that the values of drag used ($C_d = 10^{-3}$) have a minimal impact upon the cold pool’s structure, while characteristics such as an ele-
vated wind maximum and pronounced nose at the gust front are absent (Mitchell and Hovermale 1977). Because surface drag of this same order of magnitude is strong enough to dissipate the storm, this result is somewhat surprising. Therefore, additional two-dimensional simulations of flow over a flat plate and a density current were performed in order to confirm that friction was implemented correctly. No-slip, free-slip, and semislip ($C_d = 2.0 \times 10^{-2}$) lower boundary conditions were used. Results of the density current simulations were comparable to what would be expected in free-slip (e.g., Droegemeier 1985; Droegemeier and Wilhelmson 1987) versus no-slip/semislip (e.g., Mitchell and Hovermale 1977; Droegemeier 1985) conditions, and thus surface drag appears to be functioning properly.

Because no major differences are evident in the magnitude of physical mixing near the ground in the friction and free-slip control run, it appears that the small influence on wind speed in the lowest few grid levels is the dominant cause of changes in the character of mesocyclone cycling. Compared to the control run, maximum surface wind speeds behind the gust front are reduced 2%–3% for $C_d = 2.5$ and $5 \times 10^{-4}$, and approximately 7% for $C_d = 10^{-3}$. A comparison of the position of the gust front in each of the friction runs against that of the control run supports this conclusion. As the drag coefficient is increased, the gust front in each simulation at 3600 s becomes oriented in a slightly more southwest to northeast direction, suggesting that the cold pool’s motion is restricted by the small reduction in horizontal velocity at the lowest grid level.

The effect of surface friction on surface mesocyclone intensity varies with the magnitude of the drag coefficient. In the case of the highest drag ($C_d = 10^{-3}$) for which a storm could be sustained, maximum surface vorticity in the first cycle is reduced by approximately 15% compared to the control run. When the drag coefficient is reduced by half ($C_d = 5 \times 10^{-4}$) and the storm begins to cycle, maximum surface vorticity increases by 36% over the control run. When the drag coefficient again is reduced by half ($C_d = 2.5 \times 10^{-4}$) and the storm begins to cycle more quickly, maximum surface vorticity diminishes to approximately the same magnitude as in the control run.

This sensitivity of mesocyclone strength to drag coefficient suggests that there is an “optimum” value of friction (approximately $C_d = 5 \times 10^{-4}$) that maximizes the strength of the mesocyclone for this particular simulation. In this “optimal” case, maximum values of horizontal surface convergence increase by 15% relative to the first cycle of the control run, and maximum values of near-ground horizontal vorticity (<500 m) are also 23% larger. Interestingly, vertical vorticity stretching and near-ground horizontal streamwise stretching are not significantly different from the control run. The similarity of these effects most likely results from the initially smaller values of surface vertical vorticity and the increased importance of crosswise vorticity produced by the effect of friction. However, the length of time over which similar values of the vorticity occur is approximately twice as long as in the control run, thereby eventually producing a stronger mesocyclone but delaying the first occlusion by almost 3600 s.

When the drag coefficient is smaller ($C_d = 2.5 \times 10^{-2}$) than the “optimal” value, the maximum surface convergence and near-ground horizontal vorticity are within 3% of the control run’s first cycle, while vertical vorticity stretching and near-ground streamwise horizontal vorticity stretching are reduced by 14% and 27%, respectively. Other than these differences and the resultant weaker mesocyclone, this simulation is qualitatively similar to that in which $C_d = 10^{-3}$.

When the drag coefficient is larger ($C_d = 10^{-3}$) than “optimal,” maximum horizontal surface convergence and maximum near-ground horizontal vorticity are reduced by 9% and 23%, respectively, compared to the first cycle of the control run. Unlike the optimal case, this magnitude of drag appears to decrease the surface winds enough to negate the enhanced convergence associated with the friction-induced turning of the wind toward low pressure. Maximum values of vertical vorticity stretching and streamwise horizontal vorticity stretching also are reduced by 57% and 53%, respectively. In this case, the near-ground mesocyclone is never able to intensify sufficiently to allow the occlusion process to begin. The gust front remains oriented approximately north–south throughout the simulation, even during times of near-ground mesocyclone intensification when the RFD would normally force it eastward (Fig. 11a). This is reflected at upper levels by a unicellular updraft (Fig. 11b) that is unable to transform into a dual-maxima structure (Adlerman et al. 1999) throughout the entire simulation.

Because surface drag slows or stops the cyclic evolution of our simulated storm by retarding surface flow and affecting the associated vorticity dynamics near the ground, it seems plausible that any process that increases the magnitude of low-level downdrafts and resultant surface winds might counter this effect. The use of ice microphysics was shown to produce such a result, so we repeated two of the surface drag simulations, which were made using warm rain physics, this time using the ice physics parameterization. When $C_d = 5 \times 10^{-4}$, the evolution is speeded up significantly compared to the warm rain surface drag simulation. Three cycles (instead of two) are observed, with each transition occurring approximately 500 s earlier than in the control run. However, the speedup has a detrimental influence upon the strength of the mesocyclone, with maximum surface vorticity reduced by approximately 17% compared to the same run without ice physics. When $C_d = 10^{-3}$, the simulation remains very similar to the warm rain case. No cycling is observed during the entire model run, and it appears that surface drag still dominates over the effect of the stronger surface outflow. In this case however, a more optimal balance between the competing effects
Fig. 11. Horizontal cross section of vertical velocity at (a)\( z = 50 \) m and (b)\( z = 4 \) km at\( t = 7500 \) s for (left) the control run and (right) the surface friction run with \( C_d = 0.001 \). Isoline of 1 g kg\(^{-1}\) rainwater-mixing ratio is indicated by the single dark contour. Grid-relative wind vectors are indicated. Contour interval of vertical velocity is (a) 0.25 m s\(^{-1}\) and (b) 3.0 m s\(^{-1}\).

of ice physics and friction appears to be achieved, with maximum surface vorticity increasing by 21% over the same run without ice physics. As might be expected, it appears that the inclusion of ice physics shifts the “optimum” value of surface drag to a higher value. Clearly more work is needed to identify a physically appropriate representation for surface friction in cloud-resolving models.

6. Summary and discussion

We have shown that cyclic mesocyclogenesis simulated using a three-dimensional numerical model can be quite sensitive to some physical and computational parameters. A simulated supercell that undergoes repeated mesocyclone cycling at horizontal grid spacings of 1 km and smaller becomes a nearly steady-state, unicellular storm at a grid spacing of 2 km. Decreasing the minimum vertical grid spacing at the ground tends to speed up the cycling process, while increasing it has the opposite effect. Ice microphysics is shown to cut short the initial cycling, while both simple surface friction and increased numerical diffusion tend to slow it down. Combining competing effects (i.e., ice microphysics with friction) tends to bring the simulation back to the
evolution found in the control run. Although the observed variations in storm structure might be considered relatively minor given the range of sensitivities investigated, from the perspective of small-scale predictability they are not.

The orderly variations in the timing of mesocyclone cycles (Fig. 2) suggest that a common mechanism influences storm dynamics and controls cycling. For example, because the grid spacing has a direct influence on the magnitude of simulated gradients, one might assume that the inability to capture the location and strength of these gradients prevents or alters cycling. However, the explanation is slightly more complex and involves feedback processes involved with the cycling process itself.

As described in Adlerman et al. (1999), mesocyclone occlusion involves a series of events, initiated by the development of a strong RFD that not only intensifies the near-ground mesocyclone, but also influences the motion of the gust front that forces development of secondary updraft maxima above. Because these new updrafts also rotate, they induce dynamic pressure gradients that encourage further development along the surging gust front, eventually forming a new updraft–mesocyclone to the east or northeast of the previous one. At the same time, the occluding near-ground mesocyclone intensifies, forcing an occlusion downdraft that merges with the RFD. Eventually, the old near-ground mesocyclone is surrounded entirely by downdraft air and decays, while the new updraft and associated mesocyclone intensify farther to the east.

This scenario allows for several feedbacks that may modulate the frequency and duration of cycling. For example, the RFD must be strong enough to initiate cycling, but not too strong; otherwise, the gust front moves too far to the east and cuts the storm off from its inflow. At the same time, the development of the occluding mesocyclone (initiated by the RFD surge) tends to initiate a sequence of events that signals the end of a cycle. Because vortex intensification (Adlerman et al. 1999) depends upon a variety of dynamical influences that involve gradients of horizontal and vertical velocities and buoyancy, the length of a cycle will be determined partly by balances among the above. However, our results suggest that the configuration of a numerical model influences all of the important dynamics (e.g., gradients of vertical velocity, equivalent potential temperature, or rainfall) to a degree that may overwhelm any intrinsic cyclic behavior.

We have tabulated the maximum values of those derived quantities that were discussed in the text (Table 2) for comparison among the simulations. It is important to note that these quantities are derived from 5-min data, are not domain wide, and cover multiple mesocyclone cycles in some cases. Therefore, some discrepancies will exist, especially when compared with single-cycle maxima or domain-wide 1-min data. For example, the maxima in surface vorticity, calculated only in the relevant area of the domain (i.e., that subsection that encompasses the entire storm of interest) from 5-min data, are 64, 25, and $12 \times 10^{-3}$ s$^{-1}$ for the 500 m, 1 km, and 2 km storm simulations, respectively (Table 2). Maxima in domain-wide low-level vorticity (<2 km) calculated from 1-min data for the same runs are 96, 36, and $22 \times 10^{-3}$ s$^{-1}$, respectively (Fig. 6).

We note that the early numerical simulations of deep convection, which established the importance of indices such as the bulk Richardson number (BRN) (Weisman and Klemp 1982), were performed at a horizontal grid spacing of 2 km, suggesting that cyclic behavior likely would not be observed. However, a follow-up study at 1-km grid spacing (Weisman and Klemp 1984), although conducted with different wind profiles, states that cyclic behavior was observed at high shears ($U_*, > 35$ m s$^{-1}$). We speculate that this may have been an early indication of numerical model sensitivity to horizontal grid spacing in this context.

From our horizontal grid-spacing experiments, it appears that modeling of explicitly resolved convective storms may, in some cases, require a grid spacing less than 1.5 km in order to adequately capture cyclic mesocyclogenesis and perhaps other unsteady processes. Although most modern idealized storm simulations are well below this threshold (e.g., Grasso and Cotton 1995; Wicker and Wilhelmson 1995; Atkins et al. 1999), recent attempts at storm-scale prediction (Droegemeier 1997; Carpenter et al. 1997, 1998, 1999; Hou et al. 2001) are not. As computing capabilities increase and storm-scale numerical weather prediction moves toward operational implementation, it will be important to realize that the accurate characterization of storm morphology and evolution may require grid spacings of 1 km or less, even in the context of ensemble methodologies.

This study also suggests that, even at 500-m horizontal grid spacing, model resolution may be insufficient to allow the timing and motion of mesocyclone cycles to converge to an asymptotic solution. Because the timing differences between the 500- and 105-m horizontal grid spacing tests are substantial (e.g., 900 s for the time of the second occlusion), it remains unknown at what resolution numerical convergence can be achieved. Likewise, the amount of vertical resolution required remains an open question. When computing limits allow, non-nested numerical simulations at even smaller horizontal and vertical grid spacings (<100 m) will be necessary to answer this question. The calculation of total resolved kinetic energy might serve as a guide, as this quantity should increase less quickly with finer resolution if most of the energetic small scales are resolved on the grid scale.

The problem of reproducibility among numerical model simulations, which makes difficult the verification of published results even when model configuration is described with reasonable completeness (Richardson 1999), is becoming increasingly important as models
TABLE 2. Maxima of surface horizontal convergence \(10^{-3}\) s\(^{-1}\), near-ground horizontal vorticity \(10^{-3}\) s\(^{-1}\), surface vertical vorticity \(10^{-3}\) s\(^{-1}\), surface buoyancy gradient \(10^{-5}\) s\(^{-2}\), near-ground vertical vorticity stretching \(10^{-5}\) s\(^{-2}\), and near-ground streamwise stretching \(10^{-5}\) s\(^{-2}\) for the horizontal grid spacing experiments, vertical grid spacing experiments, and changes in model physics and parameters. Data is taken only in the relevant area of the domain from 5-min history files between 3600 and 12 600 s.

<table>
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<th>Surface horizontal convergence (10^{-3}) s(^{-1})</th>
<th>Near-ground horizontal vorticity (10^{-3}) s(^{-1})</th>
<th>Surface vertical vorticity (10^{-3}) s(^{-1})</th>
<th>Surface buoyancy gradient (10^{-5}) s(^{-2})</th>
<th>Near-ground vertical vorticity stretching (10^{-5}) s(^{-2})</th>
<th>Near-ground streamwise vorticity stretching (10^{-5}) s(^{-2})</th>
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grow in sophistication and is highlighted by our results. Especially vexing is the fact that the same model, with identical initial conditions, can yield significantly different solutions as a result of small changes in basic parameters, physical parameterizations, and even the size of the time step (Xu et al. 2001). As a result of these difficulties, it is not certain whether the sensitivities described in this study might also apply to other cloud models. Only after similar storm-scale sensitivity tests are conducted over a variety of numerical models will we be able to generalize such results with confidence.

Perhaps the ultimate test of understanding is the ability to predict with accuracy and reliability. For the atmospheric and computational sciences, the explicit numerical prediction of deep convective storms and their wintertime counterparts—including the type of cyclic behavior described in this paper as well as other specific features—represents one of the most significant scientific and operational challenges for the next few decades (Lilly 1990; Droegemeier 1997). Yet, it is a challenge being embraced via a community-wide model development initiative (Dudhia et al. 1998), and one that holds the promise of yielding tremendous benefits for society.

Following early work aimed at predicting the mode of convection and other basic storm attributes using a single environmental sounding (e.g., Brooks et al. 1993; Janish et al. 1995; Wicker et al. 1997), several recent studies have confirmed that cloud-resolving numerical models, when initialized with finescale radar and other observations, are capable of predicting explicitly those storm features and processes that heretofore have only been simulated in a general sense (e.g., Droegemeier 1997; Sun and Crook 1998; Crook and Sun 2001; Wang et al. 2001; Xue et al. 2001, 2002; Weygandt et al. 2002a,b). In light of the types of sensitivities demonstrated in the present paper, along with numerous other factors, the operational implementation of storm-scale NWP most likely will be stochastic, involving the use of variable-physics/parameters (e.g., Stensrud et al. 2000; Hou et al. 2001) and variable initial-condition (e.g., Hou et al. 2001) ensembles. Thus, an understanding of solution variability and sensitivity is paramount.
for the future, and in an upcoming paper we will examine the environmental conditions necessary for cyclic storm behavior.

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