The Influence of Eight Basic Environmental Parameters on the Low-Level Rotation Characteristics of Simulated Convective Storms

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1. Introduction

Improved knowledge of the environments that produce convective storms is critical to weather forecasters. Under the right balance of thermodynamic and kinematic conditions, a storm can develop low-level rotation and, sometimes, tornadoes. This paper explores the environments that lead to convective storms with large amounts of low-level rotation, which may be related to tornadoes.

Droegemeier et al. (1993) described the relationship between storm relative environmental helicity (SRH) and updraft rotation, showing that storms in large SRH environments are longer-lived, with increases in SRH corresponding to increases in both mid-level and low-level vorticity (i.e., below 1.14 km). Mesocyclones apparently are strongest when "the largest shears are confined to the shallowest depths" (Adlerman and Droegemeier 2005).

Storm responses to bulk atmospheric properties such as convective available potential energy (CAPE) or 0-6 km wind shear (e.g., Weisman and Klemp 1982, 1984) are reasonably well understood. More recently, numerical modeling studies have shown that storm morphology and evolution are influenced by heights of the lifting condensation level (LCL) and level of free convection (LFC; McCaul and Cohen 2002), the vertical distributions of buoyancy and shear (McCaul and Weisman 2001), and even cloud base temperature (McCaul et al. 2005). These studies have demonstrated the need for a parameter space approach to understanding overall storm evolution.

Table 1. Basic environmental parameters used in this study.

Parameter	Value(s)
Bulk integrated pseudoadiabatic CAPE	800, 2000, 3200 J kg^{-1}
Bulk vertical wind shear (radius of semicircular hodograph)	8, 12, 16 m s^{-1}
Shape of buoyancy profile	Two variations per CAPE
Shape of shear profile	Two variations per CAPE
Height of the LCL	0.5 km or 1.6 km
Height of the LFC	0.5 km or 1.6 km
Precipitable water (PW)	Roughly 30 mm or 60 mm
Mean free tropospheric relative humidity (FTRH)	Fixed, 90%

This work extends the results of the COnvection Morphology PArameter Space Study (COMPASS; McCaul and Cohen 2002), an eight-dimensional parameter space study, to examine low-level rotation in isolated, discrete simulated storms. We present additional results, such as properties of the updrafts, downdrafts, etc., since a storm's low-level rotation is intimately related to other aspects of storm character.

2. Data and Methodology

The experiments presented herein are part of a 216 simulation subset from the COMPASS archive. The simulations were performed with the Regional Atmospheric Modeling System (RAMS), version 3b (Pielke et al. 1992; Walko et al. 1995), with additional modifications as in McCaul et al. (2005). The eight variables that define the COMPASS parameter space (Table 1) were chosen to represent the minimum number of decisions required to construct an idealized atmospheric profile. Storms are initiated using a moist, LCL-conserving

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thermal bubble in a homogeneous 75 × 75 km horizontal domain. Full model output is saved every 5 min for each 2 h simulation.

We consider here 139 simulations that produced a discrete right-moving storm with a mean updraft velocity of at least 10 m s^{-1} in the second hour. Left-moving storms have been documented but are given only brief mention here. The vorticity at the lowest model level, 126 m AGL, is represented by "VMAX0". As in Kirkpatrick et al. (2006), the 139 simulated storms are binned into 72 "supercells" and 67 "nonsupercells." A storm is considered to be a supercell if: (a) its mean mid-level vorticity is at least 0.01 s^{-1}, averaged at each 5-min interval over the simulation's second hour; and (b) its mean linear updraft-vorticity correlation coefficient (Weisman and Klemp 1984) is 0.4 or greater over the same time period. Any storm not meeting both these criteria is considered a nonsupercell. These conditions admittedly are arbitrary, and some marginal supercell storms with strong rotation but low correlation coefficients may be excluded as a result.

Our horizontal grid spacing, 500 m, is insufficient to resolve tornado circulations explicitly. Thus, we cannot label our storms with strong low-level vorticity (high VMAX0) as "tornadic" storms. The amount of vorticity may also be a function of the chosen grid spacing (either horizontal or vertical). However, we believe our simulations identify environments in which increased low-level (and mid-level) rotation is present generally, and the findings compare well to some of the "proximity sounding" studies that have identified trends in environmental conditions conducive to supercells and to tornadoes (e.g., Rasmussen and Blanchard 1998; Craven et al. 2002).

3. Results and Discussion

The 72 supercells are further grouped into 23 "high" VMAX0 (>= 0.02 s^{-1}) and 49 "low" VMAX0 simulations. The groups reveal distinct differences between the environments of supercells with VMAX0 above and below the threshold value (Table 2). The Student's *t*-test finds that averages of four of the eight input parameters are "significantly" different between the two sets: CAPE, hodograph radius, LCL, and LFC. FTRH (Table 1) is held

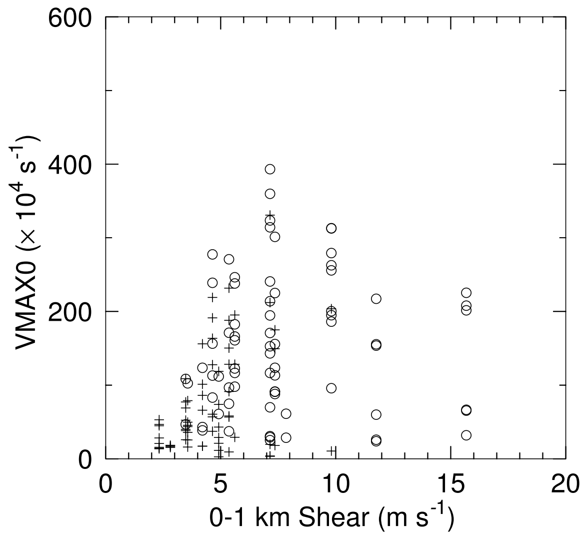

Fig. 1. Low-level (0-1 km) shear vs. VMAX0 for the 72 supercell simulations (circles) and 67 non-supercells (crosses).

constant, and the differences in values of the three other input parameters are not significant, even at the 90% level. Although not statistically "significant," one might expect the vertical concentration of buoyancy to exert some control on VMAX0; this particular parameter will be discussed below. Also in Table 1 are average values of other storm properties.

Storms with high VMAX0 tend to exist in environments with high values of bulk pseudoadiabatic CAPE. There is also a marked increase in CAPE in the 0-3 km AGL layer ($CAPE_{0-3}$). Increased $CAPE_{0-3}$ has been identified by Rasmussen (2003) as important in identifying environments favorable for strong (F2 or greater) tornadoes. Although the linear correlation between VMAX0 and $CAPE_{0-3}$ for the supercells is weak (r=0.39; Table 2), high VMAX0 storms tend to prefer large amounts of $CAPE_{0-3}$.

The increase in $CAPE_{0-3}$ seems to imply that the low-level buoyancy concentration is important; however, differences in level of maximum buoyancy are not statistically significant between the high and low VMAX0 supercell groups. To clarify these findings, we examine 17 pairs of supercells with only the buoyancy profile changed. In these pairs, concentrating buoyancy closer to the LFC leads to an average 75% increase in VMAX0. In six of the pairs, VMAX0 was more than doubled when buoyancy was "concentrated" rather than "distributed". This is a case where, because of the inclusion of several distinct vorticity-trend regimes, the bulk statistical trends may not present a complete description of the relationships that exist between sounding parameters and storm morphology.

The average radius of the hodograph is greater by 1.4 m s^{-1} in high VMAX0 simulations, although the vertical level of maximum *v*-wind does not change appreciably. This hodograph radius increase corresponds to roughly 2 m s^{-1} of additional bulk shear and a 2.5 m s^{-1} longer hodograph in the 0-6 km layer. Generally speaking, as hodograph length increases, so does the bulk shear (a series of 661 supercell cases collected by M. Bunkers showed a 0.61 correlation between bulk shear and hodograph length).

Even though there is no noticeable *linear* correlation between VMAX0 and the low-level shear, the low-level (0-1 km) shear is also increased by 1.3 m s^{-1}. Fig. 1 suggests, however, that there may be a preferred range of low-level shear that results in the highest VMAX0. Below this range, there is insufficient shear for supercells generally, and above this range, low-level updrafts are excessively sheared and struggle to persist (although they may retain supercell characteristics). Interestingly, the range suggested by Fig. 1, about 6-10 m s^{-1}, resembles the median 0-1 km shear found by Thompson et al. (2003) in a study of model-based proximity soundings for both weak (F0-F1, 8.1 m s^{-1}) and violent (F2-F5, 9.8 m s^{-1}) supercell tornadoes. It is also similar to the 0-1 km shears that maximized near-surface vorticity in straight (8.0-9.5 m s^{-1}) and curved (10 m s^{-1}) hodograph simulations of Weisman and Klemp (1982 and 1984, respectively).

The simulations that produce more VMAX0 have slightly lower LCLs and LFCs when compared to their low VMAX0 counterparts. Observational studies have suggested that environments with a low LCL (Rasmussen and Blanchard 1998) and a low LFC (Davies 2004) are preferred for strong, violent tornadoes. A low LCL, which implies a relatively shallow layer of subsaturated air beneath cloud base, can reduce the likelihood of the updraft being undercut by the storm's forward-flank outflow. A low LFC allows CAPE to be concentrated closer to the ground, thus leading to increased strength of the low-level updraft. Stronger low-level updrafts can more easily convert environmental vorticity into rotation, thus increasing VMAX0.

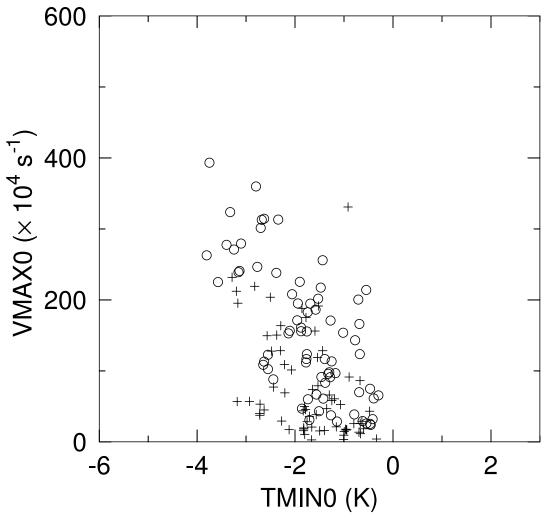

Fig. 2. Average second-hour surface temperature deficit (TMIN0; i.e.,"cold pool strength") vs. VMAX0 for the 72 supercell and non-supercells, with symbols as in Fig. 1.

Newton and Fankhauser (1975) showed that storms with larger diameters deviate further from the mean winds. This, in turn, increases SRH and produces higher VMAX0. The high VMAX0 storms also produce more hail and rain at the surface, and have larger and stronger cold pools (Fig. 2), which may suggest that enhanced baroclinity at the surface is aiding generation of horizontal vorticity (which is then tilted into the vertical). The increased cold pool strength and size may also be affecting storm propagation. More work is needed to clarify whether the increased deviate motions (not shown) in high VMAX0 cases are the result of interactions with the environmental shear or with storm-generated outflow.

The finding that high VMAX0 storms prefer environments with low LFCs appears to contradict the production of stronger cold pools in high VMAX0 cases. One tentative hypothesis is that in our low LFC simulations, reduced θ_e air exists at lower heights, and is more easily mixed to the ground by the downdraft. This quandary also presents opportunities for further analysis.

Table 2. Comparison of various mean parameters for *supercells only* with "high" (>= 0.02 s^{-1}) and "low" (< 0.02 s^{-1}) VMAX0, with *t*-test confidence interval (CI) if above 90%. "Correlation" is the linear correlation between VMAX0 and the parameter. The seven parameters in italics are seven of the eight basic parameters used to initialize COMPASS soundings.

	High VMAX0 (n = 23)	Low VMAX0 (n = 49)	CI (%)	Correlation
Bulk CAPE (J kg^{-1})	***2264***	***1832***	***90***	***0.45***
Hodograph Radius (m s^{-1})	***15.3***	***13.6***	***99***	***0.40***
Level of max buoyancy (km)	***5.44***	***5.41***	--	***0.18***
Level of max v-wind (km)	***5.30***	***5.61***	--	***0.06***
LCL (km)	***0.64***	***0.90***	***95***	***-0.19***
LFC (km)	***0.93***	***1.22***	***95***	***-0.24***
T_{LCL} (°C)	***17.6***	***16.2***	--	***0.01***
CAPE 0-3 km (J kg^{-1})	260	185	99	0.39
0-1 km shear (m s^{-1})	8.7	7.4	90	0.05
Bulk Richardson Number (BRN)	38	47	--	-0.01
Maximum updraft speed (m s^{-1})	39.2	32.9	90	0.45
Updraft speed at 2 km (m s^{-1})	15.8	10.2	99	0.84
Updraft area at 5 km (km^2)	69.5	50.1	99	0.55
Midlevel vorticity (× 10^4 s^{-1})	325	248	99	0.75
Vorticity at 126 m AGL (× 10^4 s^{-1})	266	101	99	1.00
Minimum pressure perturbation (mb)	-1.89	-1.11	99	-0.84
Surface hail mixing ratio (g kg^{-1})	0.18	0.08	95	0.50
Surface rain mixing ratio (g kg^{-1})	6.93	5.19	99	0.55
Surface cold pool area (km^2)	83	46	99	0.47
Surface cold pool strength (°C)	-2.5	-1.4	99	-0.70

To further study the distribution of vorticity in our simulations, vorticity histograms were constructed (bottom panels in Fig. 3) by accumulating the vorticity values at each grid point in the domain at 5 min intervals during the second hour. Presented in Fig. 3 are statistics from one triad of simulations with only the LCL and LFC heights changed. Although the high LCL-LFC simulation (lower right panel) produces the largest mid-level (i.e., 5-8 km AGL) vorticity values, it produces the least amount of vorticity in the lowest kilometer. The low LCL, low LFC case (lower left) produces substantially more vorticity at low levels than either of the other two simulations (the low LCL, high LFC simulation is shown in the middle panel). Interestingly, the high LCL-LFC case produces high values of *negative* vorticity, suggesting that a left-moving storm (not shown) in the domain is rotating strongly at low levels. At middle levels, it appears that the low LCL-high LFC regime produces equal amounts of positive and negative vorticity. The low LCL-LFC simulation does produce some negative vorticity at the lowest model level, and this may be associated with a gust front (see, e.g., the blue contours [which represent negative vorticity] in the upper left panel of Fig. 3).

4. Summary

Simulated convective storms that produce large amounts of low-level vorticity are found to exist predominantly in environments with:

- Large CAPE;
- Steep low-level lapse rates;
- Long hodographs;
- Large amounts of low-level shear; and
- Low LCLs and low LFCs.

This is consistent with studies of convective storm proximity soundings, which have shown skill in identifying environmental conditions supportive of supercells and tornadoes. It is noteworthy that our findings are harmonious with these observational studies even when our model configuration is inadequate for resolving actual tornadoes.

Although certain "bulk" statistics (e.g., CAPE, hodograph radius, or updraft speed at 2 km; Table 1) conform with expected trends in VMAX0, some results are more difficult to interpret. This suggests that more detailed analyses of general statistical trends found in some observational studies may need to be performed, as there may be important storm sensitivities to some environmental parameters that become masked when many cases from many different environmental regimes are combined (as demonstrated here with the buoyancy profile shape).

The results herein should be useful for tornadogenesis modelers in the selection of ambient profiles that will produce storms with large amounts of low level vorticity. Further simulations at LES-scale of certain cases having large cyclonic VMAX0 could yield insight into the ways mesocyclone-scale vorticity leads to tornadogenesis. Additional work can include decomposition of terms in the pressure perturbation equation (Rotunno and Klemp 1982), as well as parcel trajectory analyses of cases in the COMPASS archive. These efforts will help examine the physical processes that lead to the modeled phenomena near the surface.

5. Supplementary Information

For additional information on COMPASS, see *http://space.hsv.usra.edu/COMPASS*.

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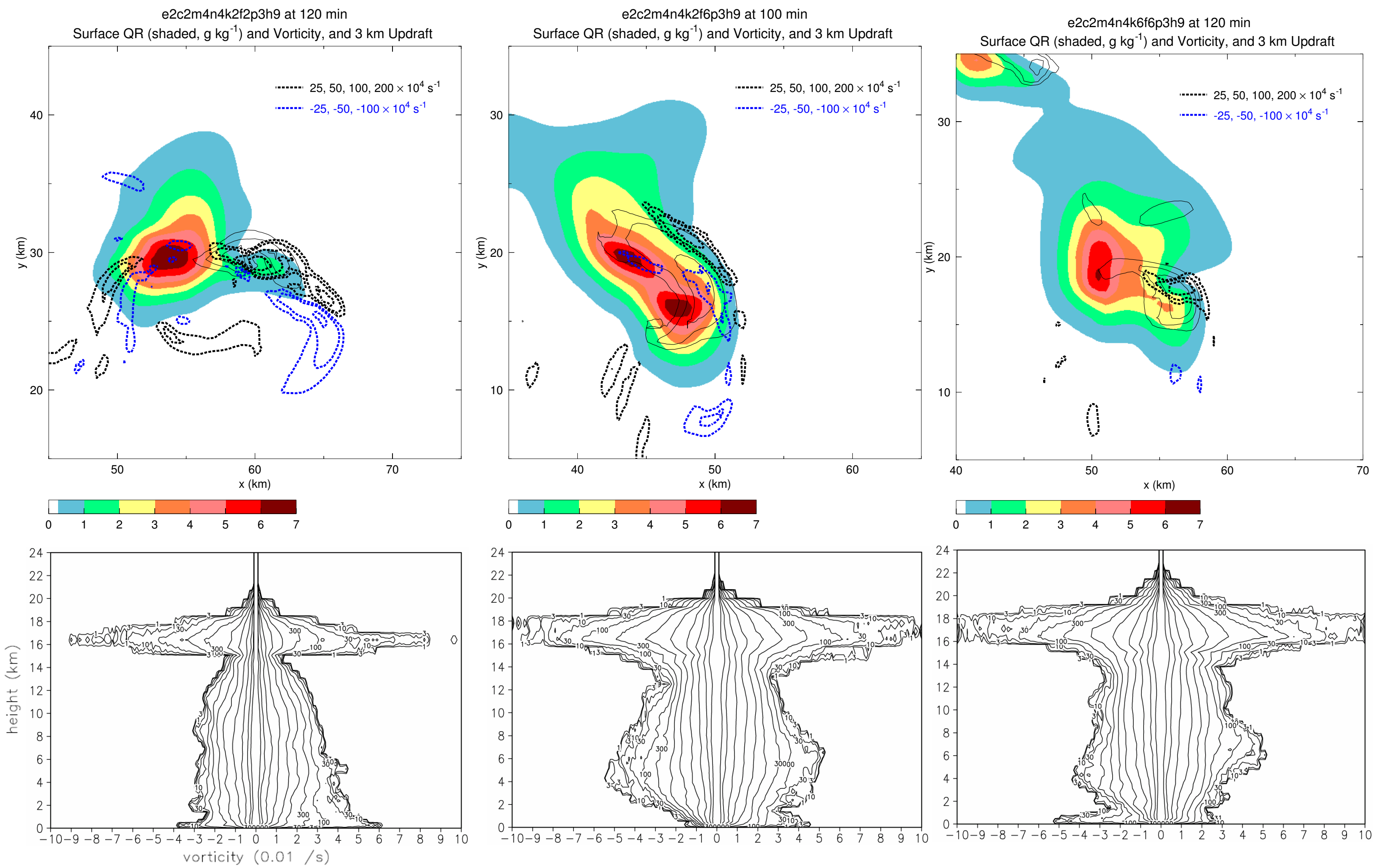

Fig. 3. Sample of three COMPASS simulations (2000-CAPE, 12 m s^{-1} hodograph radius, concentrated buoyancy and shear, PW=30 mm, FTRH=90%) with varied LCL and LFC. Left column has LCL=LFC=0.5 km; middle column has LCL=0.5 km, LFC=1.6 km; and right column has LCL=LFC=1.6 km. Top row shows surface rainwater mixing ratio (shaded), vorticity (dashed contours in black [positive] and blue [negative]), and 3 km updraft (solid contours; 2, 5, 10, 20 m s^{-1}). Bottom row are vorticity histograms as described in the text.