4.2 ON THE EXISTENCE OF CONVECTIVE ROLLS IN THE CONVECTIVE REGION OF SQUALL LINES

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1. INTRODUCTION

Many strong, mature squall lines are composed of two distinct regions: the convective region, and the stratiform region. Of main interest here is the convective region. It is (typically) characterized by the highest radar reflectivity values, the strongest rainfall rates, and the highest updraft velocities. This region is often found on the leading portion of the squall line, i.e., it is typically found on the downwind (relative to mid-level flow) side of the squall line, where low-level air first enters the system.

The convective region is often considered to be composed of deep convective cells in various states of development. That is, the classical cumulonimbus structure and lifecycle of Byers and Braham (1948) is usually considered to be the dominant process in the convective region. While this model may be representative of some squall lines, several recent studies suggest that air in this region primarily ascends as a layer-like upward-sloping slab in the lower troposphere from which discrete cumulonimbus cells then emerge in the mid- to upper-troposphere (e.g., Kingsmill and Houze 1999; Bryan and Fritsch 2000; Rogers and Fritsch 2001; Mechem et al. 2002; James and Fritsch 2003). The processes that occur in this layer-dominated (i.e., *slabular*) mode of overturning are still being investigated, and many questions remain.

The purpose of this paper is to describe a particular mode of overturning that can occur in some slabular squall lines. In a recent series of high-resolution numerical model simulations, it was found that the ascending low-level layer sometimes overturns with a structure best described as convective rolls. This type of overturning is, in some sense, analogous to horizontal convective rolls in the planetary boundary layer (PBL), which are sometimes visible as cloud streets in satellite images. More specifically, the overall structure can be summarized as counter-rotating vortex tubes with axes that are roughly parallel to the shear vector.

In this preliminary analysis, the structure of the convective rolls is documented using output from a high-resolution (125 m grid spacing) numerical simulation of a squall line. A set of conditions for which this mode of overturning can be realized is proposed.

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2. DESIGN OF NUMERICAL SIMULATIONS

The numerical model used for this study is described in Bryan and Fritsch (2002) and Bryan (2002). The governing equations are integrated using the Runge-Kutta technique as formulated for compressible models by Wicker and Skamarock (2002). The model is similar in design to the height-based-core of the Weather Research and Forecasting (WRF) model (Skamarock et al. 2001). For the simulation presented here, the configuration uses the Kessler (1969) microphysics scheme and the Deardorff (1980) subgrid turbulence parameterization.

The model domain is 300 km long in the across-line direction, 60 km long in the along-line direction, and 18 km deep. Both the horizontal and vertical grid spacing is 125 m. The lateral boundary conditions are open-radiative in the cross-line direction, and periodic in the along-line direction. The analytic temperature and moisture profiles of Weisman and Klemp (1982) are used to define a horizontally-homogeneous environment. A line thermal with a maximum amplitude of +2 K is used to initiate the squall line. Small temperature perturbations within the initial line thermal allow for the development of three-dimensional circulations. The initial wind profile features 10 m s^{-1} of shear over the lowest 2.5 km in the across-line direction, with no initial shear or flow in the along-line direction.

Output after 180 min of simulation time is presented here. For more information about this simulation, and for a comparison to other environments, the reader is referred to Bryan et al. (2003); this paper also provides a justification for the use of such high resolution to study the structure of deep moist convection.

3. STRUCTURE OF CONVECTIVE ROLLS

In the most basic sense, convective rolls can be characterized as a series of counter-rotating vortex tubes. Consequently, there is a spatially- and temporally-continuous updraft along the axis of the rolls, with a corresponding continuous downdraft parallel to, but separate from, the updraft. This conceptual model is most familiar to meteorologists through the existence of cloud streets, the linear cloud bands at the top of the atmospheric boundary layer. An excellent schematic diagram of convective rolls (also known as roll vortices or longitudinal rolls) is presented in the review articles of Brown (1980, Fig. 5) and Etling and Brown (1993, Fig. 2), which has since been reproduced in many papers on convective rolls (e.g., Weckwerth et al. 1997, Fig. 1).

With this structure in mind – i.e., that of counter-rotating vortex tubes – we show that deep moist

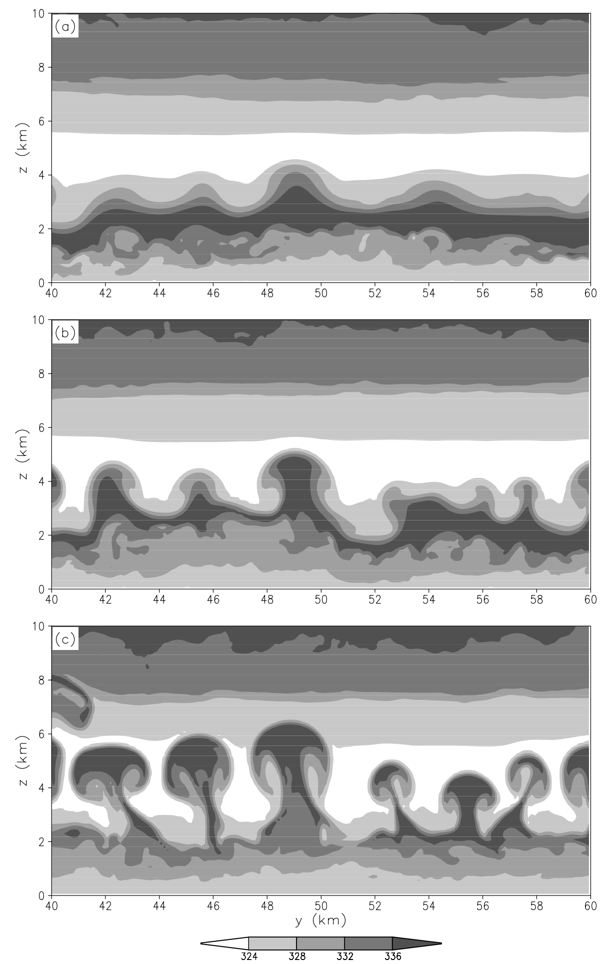

Fig. 1. Along-line cross sections of equivalent potential temperature (θ_e) illustrating the structure of roll circulations in the convective region of a numerically simulated squall line. Locations of the cross sections are (a) x=211 km, (b) x=208 km, and (c) x=205 km.

overturning in the convective region of squall lines can be manifested as convective rolls. Along-line cross sections of equivalent potential temperature (θ_e) reveal the presence of the counter-rotating tubes. At the leading edge of the squall line, a few km behind the surface gust front, the ascending branch first becomes visible (Fig. 1a). Three km downstream (following the low-level, high-θ_e, storm-relative flow), the ascending branches of the rolls are still evident as plumes of high θ_e air extending upward from the squall line slab (Fig. 1b). At this location, descending branches are apparent, since mid-level low θ_e air is lower than its initial pre-squall-line level. Another three km downstream, the roll circulation can be readily inferred from the θ_e pattern (Fig. 1c); at this location, high θ_e air has been entrained up through the center of the roll circulation, has diverged at the top of the roll, and has descended on both sides.

The kinematic structure of the rolls is illustrated for the same three locations in Fig. 2. Wind vectors clearly reveal the ascending and descending portions of the

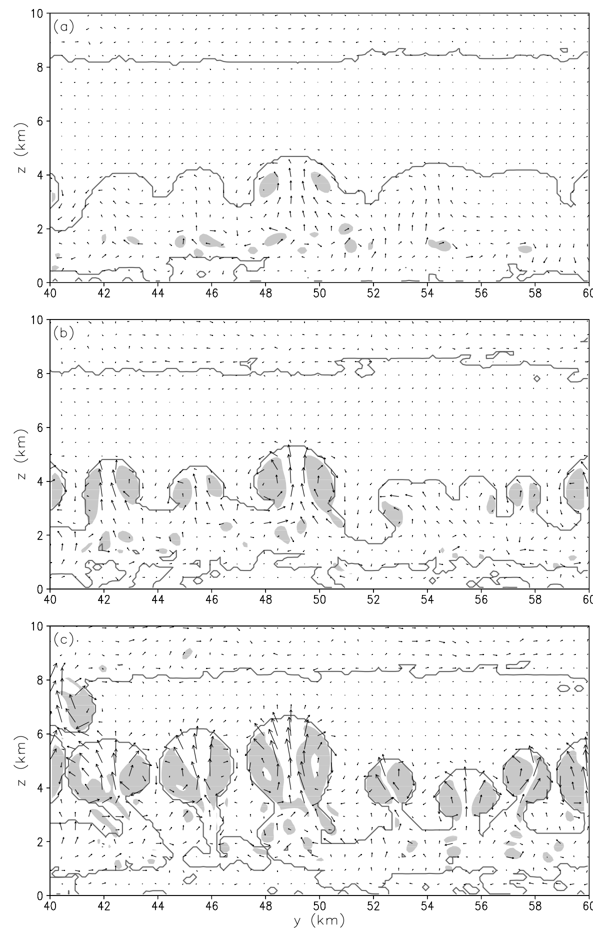

Fig. 2. As in Fig. 1, except for wind vectors. Shading indicates regions in which the absolute magnitude of horizontal vorticity is greater than $2{\times}10^{-2}$ s^{-1}. Cloud boundaries are illustrated with gray contours.

rolls. Locally high values of horizontal vorticity extend from one panel to the next, revealing that the tubes span continuously in the along-line direction. A plot of cloud top height further illustrates this characteristic (Fig. 3). Similar to shallow PBL rolls, these deep convective rolls are aligned with the vertical shear vector.

The overall structure of the overturning is remarkably similar to Rayleigh-Benard convection (c.f., Fig. 1 of Sparrow et al. 1970). In particular, the vertically-ascending plume eventually becomes wider at the top than at the bottom, with an overall mushroom-like shape. Entrainment occurs mainly along the sides of the plume. A nearly undilute core persists within the central axis of the plume.

The undilute core of the convective rolls clearly separates this mode of overturning from the classic thunderstorm cell (e.g., Byers and Braham 1948). The classic cell tends to be a fairly short-lived "pulse", with most of the entrainment occurring in the initial development of the cell (see, e.g., Blyth et al. 1988; Doswell 2001). A cloudy "wake" of mixed air is left behind by the growing cumulonimbus. In contrast, for

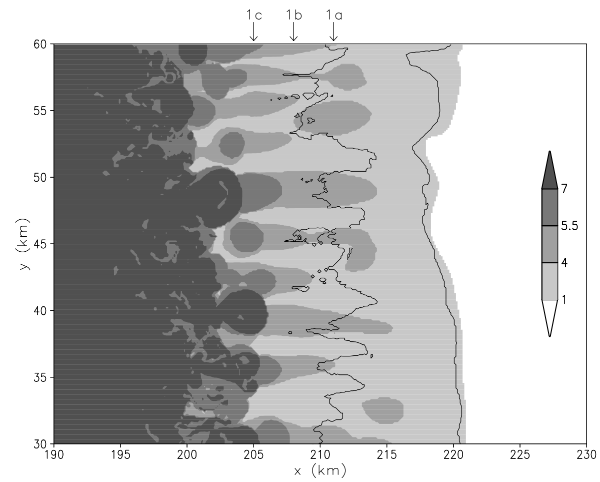

Fig.3. Cloud top height in the convective region (shaded). Only cloud with temperature warmer than –20 °C is considered. The black contour encloses regions in which the depth of vertically continuous moist absolute instability is greater than 1.5 km. The arrows at the top of the figure indicate the locations of the cross sections in Figs. 1 and 2.

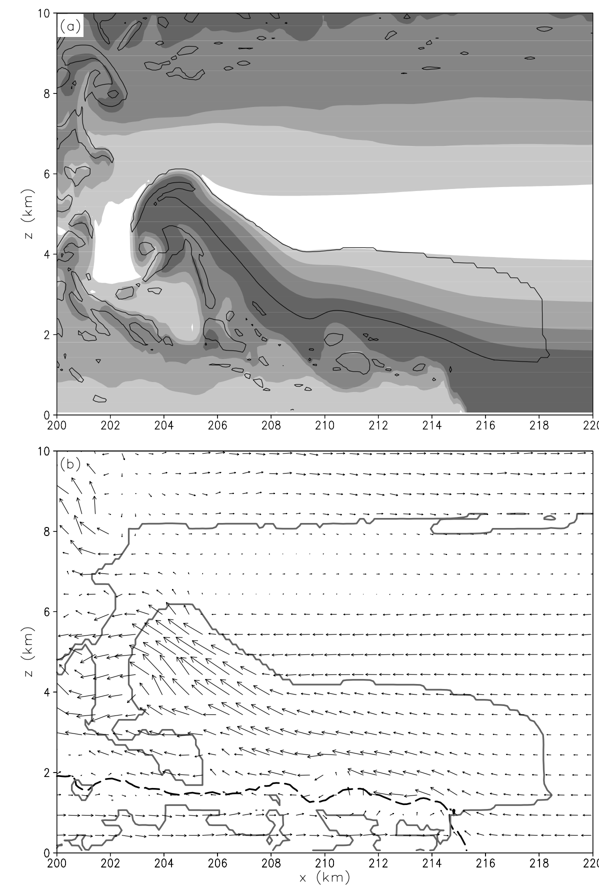

Fig. 4. Across-line cross sections at y=45.5 km, illustrating the structure of a developing plume in the ascending portion of a convective roll. (a) θ_e (shaded), with areas of moist absolute instability enclosed by black contours; and, (b) wind vectors, cloud boundaries (grey contours), and the –1.5 K perturbation potential temperature contour (dashed black contour).

the plumes noted in this simulation, an undilute stream of high θ_e air is often found in the central axis of the plume (Fig. 4). Animations reveal that plumes of undilute air can last for 10-25 min. This behavior is consistent with the notion of convective rolls, whereby an axis of ascent persists both horizontally and temporally.

4. THE DEVELOPEMENT OF CONVECTIVE ROLLS

The development of rolls is attributed to the existence of neutral or unstable (from a static stability perspective) saturated layers of air that form in the sheared layer above the squall line cold pool. These layers are created when an initially-subsaturated and conditionally unstable *layer* of air is lifted by the squall line's surface-based cold pool (Bryan and Fritsch 2000). In this simulation, a horizontally-continuous slab of moist absolute instability (contoured regions in Figs. 3 and 4) is created by dynamically-generated ascent associated with the squall line cold pool. In this sense, the development of convective rolls in the convective region of squall lines is analogous to the development of rolls in the atmospheric boundary layer – both occur in a layer of unstable (or near neutral) thermal stratification. We also speculate that the overturning is basically a manifestation of Rayleigh-Benard instability. This is assumed based on the favorable conditions (e.g., Rayleigh number, which is ~10^4 here), the resultant structure (e.g., mushroom-shaped overturning), and the remarkably regular spacing between cells (~3 km). Further research is necessary to definitively prove this hypothesis. If the theory is applicable to moist absolutely unstable layers (MAULs), it suggests that the spacing between the rolls (and, therefore, the spacing between deep convective cells) and perhaps the size of the convective cells that emerge from the layer, are proportional to the depth of the MAUL and to the magnitude of instability (i.e., lapse rate) within the MAUL.

A characteristic of this squall line that may be necessary for the development of convective rolls is the quasi-horizontal flow in the continuous low-level MAUL. As an example, Fig. 4b illustrates how air that is initially ascending rapidly at the leading edge of the cold pool (at roughly *x*=215 km) turns towards the horizontal as it continues to flow upstream relative to the gust front. The flow is not exactly horizontal in this instance, but the flow clearly ascends less rapidly in the MAUL than at the leading edge of the cold pool or in the deep convective plumes. This seems to be an important characteristic for the development of rolls, since it prevents the immediate breakdown of the MAUL into less-organized cellular (i.e., pulse-like) overturning. In a different simulation with stronger low-level shear (17.5 m s^{-1} over the lowest 2.5 km), the near-surface air turns into the vertical at the leading edge of the cold pool, and

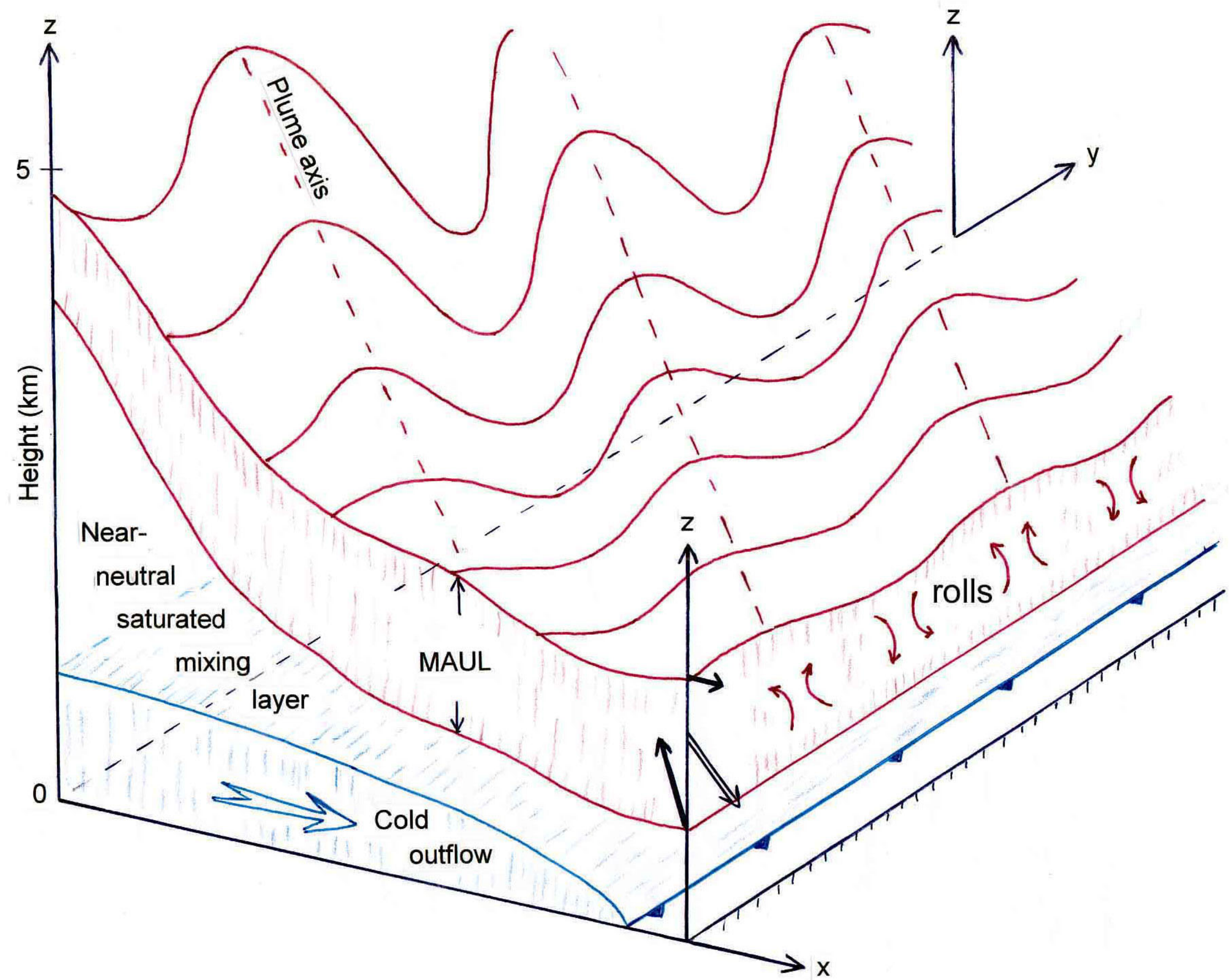

Fig. 5. Schematic of rolls in the convective region. Bold solid arrows at the top and bottom of the moist absolutely unstable layer (MAUL) indicate the ground-relative wind flow. The double-line arrow indicates the shear vector. In this schematic, the plumes axes are not perpendicular to the surface gust front (as they are in the numerical simulation); this change was made to illustrate that the shear vector may not be perpendicular to the gust front.

continues to ascend vertically above the surface gust front (not shown). This difference in structure as low-level shear is increased is consistent with the cold-pool/shear balance arguments of Rotunno et al. (1988). The MAUL in this strong-shear case breaks down into small-scale (1-2 km) eddies almost immediately, and roll circulations never develop. It appears that upright convection at the leading edge of the cold pool (i.e., the "optimal" state of Rotunno et al. 1988) is unfavorable for the development of convective rolls. Moreover, it seems reasonable to assume that there is a characteristic time scale for the creation of the roll circulations. When the saturated flow extends quasi-horizontally, as in the weak-shear case documented in this paper, the roll circulation has time to be realized.

Another aspect of the simulation highlighted here that may favor the development of convective rolls is the existence of a quiescent, horizontally-homogeneous inflow. The notion that small-scale perturbations grow the fastest has been well established (e.g., Lilly 1960). Since there are (basically) no anomalies to perturb the moist unstable state, these conditions allow time for a particular mode of overturning to be manifested – i.e., the Rayleigh-Benard instability. In this case, the rolls have a wavelength of ~3 km, which is much greater than the smallest resolvable scales in this high-resolution simulation, supporting the contention that a larger-scale instability is being manifested. To further test the hypothesis that quiescent and horizontally-homogeneous inflow conditions favor the development of rolls, we conducted another simulation in which heating was added to the lower surface. Coarser resolution (250 m grid spacing) was used due to computing limitations. In this simulation, a heterogeneous boundary layer forms due to (dry) turbulent overturning in the resulting unstable PBL. The structure of the convective region becomes more chaotic as the squall line encounters the heterogeneous PBL, which has locally higher values of heat, moisture, and momentum due to boundary layer eddies. Furthermore, the deep convective cells in the squall line become noticeably smaller than in the control simulation. This additional simulation reaffirms the concept of the preferential growth of small-scale perturbations. More importantly, it suggests that squall lines containing deep moist convective rolls may be more likely in nocturnal environments.

The fact that PBL rolls form in daytime conditions with strong surface heating, whereas deep moist convective rolls seem to be preferred in nocturnal conditions, is not a contradiction. The two cases differ in several fundamental aspects, and should not be viewed as equivalent processes. First, PBL rolls require surface heating to provide and maintain an unstable (or near-neutral) thermal stratification. In contrast, the unstable stratification in the deep moist case forms by a completely different process that does not require the presence of surface heating. Second, and perhaps more fundamentally, the development of deep moist rolls in the convective region of squall lines is a transition process – specifically, it is the transition from a subsaturated laminar flow to turbulent moist overturning, with the rolls being the fastest-growing mode in the new state. In contrast, the PBL rolls often exist as a steady-state process; that is, they often last for several hours. Furthermore, PBL rolls form in an environment that is turbulent everywhere – i.e., they are not necessarily tied to the transition from laminar to turbulent flow. In summary, the two roll types highlighted herein have fundamentally different dynamics; in this context, it is not surprising that they can develop under strikingly different conditions.

5. CONCEPTUAL MODEL

A conceptual model (Fig. 5) for the creation, structure, and role of convective rolls in the convective region of squall lines is advanced in this section. The model presents the most salient features of roll overturning in squall lines.

First, a quasi-linear cold pool is needed to lift a layer of air to saturation. This cold pool may be generated by previous convection, or could be a component of an already well-developed squall line. A moist absolutely unstable layer (MAUL) is formed by the dynamic ascent at the leading edge of the cold pool.

In some cases, as illustrated in Fig. 5., the MAUL is overturned by convective rolls. The overall pattern of overturning is that of counter-rotating vortex tubes. The axis of the rolls is roughly parallel to the shear vector through the MAUL (analogously to PBL rolls). The shear vector in the MAUL is not necessarily perpendicular to the surface gust front, as it is in the simulation studied here. Therefore, Fig. 5. shows a case in which the rolls are oriented obliquely to the gust front, but still approximately parallel to the shear vector. It follows that, for certain shears (probably with along-line environmental wind components), the rolls could be oriented more toward being parallel to the gust front than perpendicular to it. This may play a role in the reflectivity structure of squall lines (see, e.g., James and Fritsch 2003).

Since the layer of air in which the rolls form is absolutely unstable, the ascending portion of the overturning rolls can ascend vertically as deep convective plumes. It is also noted that, since the horizontal spacing between rolls remains the same, while the depth of the roll circulation increases, it is not possible to assign a characteristic aspect ratio to the rolls studied here.

The top of the MAUL ascends vertically with the ascending plumes, as the high θ_e air ascends. The base of the MAUL, on the other hand, is eroded by turbulent mixing at the bottom and along the sides of the plumes. Ultimately, the MAUL is replaced by a nearly moist-neutral state – i.e., the stratiform region of the squall line.

Mid-level, low θ_e air primarily descends as it enters the squall line (from the front of the system). This descent is coincident with the descending portion of the roll circulations. It is also consistent with Doppler radar observations of squall lines (e.g., Zipser 1977; Knupp and Cotton 1982).

Finally, the resulting slope of the convection (from an Eulerian perspective) is about 30-45 degrees from the horizontal in the present simulation, but may be significantly lower in others. LeMone et al. (1984) found an average leading-line tilt of 20-35 degrees in convective systems observed during GATE. Such a low slope may be necessary for convective roll circulations to be realized.

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