Environmental Distinctions between Cellular and Slabular Convective Lines

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ABSTRACT

The organizational mode of quasi-linear convective systems often falls within a spectrum of modes described by a line of discrete cells on one end ("cellular") and an unbroken two-dimensional swath of ascent on the other ("slabular"). Convective events exhibiting distinctly cellular or slabular characteristics over the continental United States were compiled, and composite soundings of the respective inflow environments were constructed. The most notable difference between the environments of slabs and cells occurred in the wind profiles; lines organized as slabs existed in much stronger low-level line-relative inflow and stronger low-level shear.

A compressible model with high resolution ($\Delta x = 500$ m) was used to investigate the effects of varying environmental conditions on the nature of the convective overturning. The numerical results show that highly cellular convective lines are favored when the environmental conditions and initiation procedure allow the convectively generated cold pools to remain separate from one another. The transition to a continuous along-line cold pool and gust front leads to the generation of a more "solid" line of convection, as dynamic pressure forcing above the downshear edge of the cold outflow creates a swath of quasi-two-dimensional ascent. Using both full-physics simulations and a simplified cold-pool model, it is demonstrated that the magnitude of the two-dimensional ascent in slabular convective systems is closely related to the integrated cold-pool strength.

It is concluded that slabular organization tends to occur under conditions that favor the development of a strong, contiguous cold pool. The tendency to produce slabular convection is therefore enhanced by environmental conditions such as large CAPE, weak convective inhibition, strong along-line winds, and moderately strong cross-line wind shear.

1. Introduction

The squall line has long been a phenomenon of meteorological interest in both midlatitude and tropical regions, consisting of "a line of active thunderstorms, either continuous or with breaks, including contiguous precipitation areas resulting from the existence of the thunderstorms" according to the Glossary of Meteorology (Glickman 2000). Numerous observational, theoretical, and computational studies have elucidated many aspects of the organization and mechanics of squall lines, leading to conceptual models that focus particularly on the mesoscale characteristics of these linear convective systems (e.g., Zipser 1977; Leary and Houze 1979; Houze et al. 1989; Rasmussen and Rutledge 1993). As a tool to study mesoscale convective systems, numerical models have become extremely useful and are generally considered capable of accurately reproducing at least their mesoscale structure and evolution (Weisman et al. 1997).

To date, however, the convective-scale organization of linear convective systems remains rather poorly understood. Limitations in observing platforms and in computational capabilities have hindered the thorough investigation of convective-scale organizational processes. Except for radar-observing systems positioned very close to the convection, modern instrumentation is capable of only crude measurement of the internal structure of the convective region of squall lines. This makes it difficult to verify the results of high-resolution numerical simulations. Moreover, three-dimensional modeling itself has been constrained by computational barriers to the extent that truly cloud resolving simulations of mesoscale systems have become possible only in very recent years (Bryan et al. 2003).
Understanding the convective-scale structure and dynamics of convective systems is very important, because it is on the cloud scale that most severe weather phenomena originate and operate. Without a firm grasp of the nature of the convective-scale processes governing the evolution of convective lines, the prediction of the character of a convective event will be difficult. Additionally, the development of convective parameterizations that are well founded and appropriate relies heavily on the conceptual understanding of convective-scale processes (Kingsmill and Houze 1999).

One of the more interesting and useful measures of the convective-scale structure of a squall line is the degree to which the convective region may be described as two-dimensional. Traditionally, the squall line has been envisioned as a line of more or less discrete towers or plumes of vigorous ascent, separated by regions of weaker ascent or even descending motion (Fig. 1a). In recent years, increasing attention has been directed to the fact that convective overturning frequently occurs in a manner resembling a mesoscale slab of ascent overrunning a slab of descending air (Bryan and Fritsch 2000; Mechem et al. 2002; Fig. 1b). The fundamental distinction between approximately two-dimensional and highly three-dimensional convective lines is the focus of this paper.

Early researchers investigated squall-line behavior using observations and both analytical and numerical models, often focusing on two-dimensional flow solutions for the sake of conceptual and computational simplicity. Attempts were made to identify the fundamental building block of the squall line as a steady two-dimensional “cell,” but numerical modeling was unsuccessful in reproducing steady two-dimensional overturning in deep shear (see the review in Rotunno et al. 1988). However, Thorpe et al. (1982) obtained a quasi-steady storm in two dimensions when the environment contained strong low-level shear and weak mid- to upper-level shear, and they suggested that their solution was similar to many midlatitude squall lines. The interpretation of the long-lived two-dimensional solution of Thorpe et al. (1982) was clarified by Rotunno et al. (1988), who demonstrated that the majority of nonsupercellular squall lines consist of a long-lived system of ordinary, short-lived cells that are continually regenerated along the leading edge of the surface-based cold outflow. In highly sheared environments, lines of discrete, long-lived supercells are favored; the supercellular line contains essentially steady, three-dimensional features and is dynamically distinct from the ordinary line.

Weisman and Rotunno (2004) made clear that although the nonsupercellular squall line consists of a system of ordinary “cells,” the lifting that is said to regenerate the cells is continuous and two-dimensional along the leading edge of the squall line. In fact, the cold pool–shear balance theory of Rotunno et al. (1988) (hereafter RKW theory) is fundamentally concerned with the two-dimensional lifting produced by the cold pool–shear interaction: “for the case of a cold pool spreading in a sheared flow, optimality is defined simply as the environment that produces the deepest, most upright lifting at the leading edge of the cold pool” (Weisman and Rotunno 2004, p. 377). Even if the environmental conditions do not favor the development of an “RKW-optimal” state, a surface-based cold pool that spreads downshear (relative to the low-level shear)
will generate lifting along its leading edge (Rotunno et al. 1988; Parker and Johnson 2004a,b). Above a certain elevation (often 2–4 km), the low-level two-dimensional ascent typically breaks down into cells, plumes, bows, or other modes with significant three-dimensionality, even in “optimal” cases (Weisman and Rotunno 2004; Bryan and Fritsch 2000; Weisman et al. 1988).

It seems clear, then, that most convective lines possessing a quasi-linear, spreading outflow boundary will exhibit approximately two-dimensional ascent to some depth along the cold pool’s leading edge, and a more three-dimensional pattern of vertical velocity at higher elevations. In some instances the two-dimensional ascent may be very deep. This concept of three-dimensional overturning emerging from a low-level swath (or “slab”) of ascent is consistent with both observations (e.g., Chong et al. 1987; Jorgensen et al. 1997) and numerical simulations (e.g., Redelsperger and Lafore 1988; Trier et al. 1997; Bryan and Fritsch 2000; Weisman et al. 1988). Kingsmill and Houze (1999) and Mechem et al. (2002) refer to the two-dimensional low-level ascent as “layer lifting.”

Observed by radar, squall lines containing slablike lifting usually exhibit unbroken reflectivities in the along-line direction. A continuous rain area is consistent with the presence of a relatively homogeneous, surface-based cold pool, as surface observations typically confirm. Very often, the radar reflectivity pattern exhibits both a convective region and a trailing stratiform region (e.g., Smull and Houze 1987), although some slablike lines may have stratiform regions parallel to or ahead of the convective region (Parker and Johnson 2000). In some instances, the reflectivities in the convective region are uniformly high (>45–55 dBZ) along the line, forming an unbroken and visually impressive swath (e.g., Fig. 2a). We consider this mode, wherein the squall line has a highly two-dimensional appearance, to represent the canonical “slabular” line, although low-level slablike lifting may occur in many systems with weaker or more disorganized reflectivity patterns.

In contrast to the slabular mode, a highly three-dimensional form of organization is observed within some convective lines. In this “cellular” mode, precipitating convective elements are arranged in a line, but are separated by regions of weak or nonexistent precipitation (e.g., Fig. 2b). At the surface there may or may not be a continuous outflow boundary, but the highly discrete pattern of radar reflectivity maxima indicates that deep ascent and precipitation production is confined to the cellular cores. One well-known example of the cellular mode is a line of well-separated supercells, which occurs under conditions of strong, deep shear (Weisman et al. 1988). The supercellular line has been previously investigated and is relatively well understood (Weisman et al. 1988; Rotunno et al. 1988; Bluestein and Weisman 2000), but only a small percentage of convective lines are supercellular (Doswell 2001). It is important to note that cellular lines may or may not be composed of supercells, because a noncontinuous radar reflectivity pattern may also be generated by nonsupercellular modes that are dynamically very different. In this study, it is the discreteness or discontinuity of the intense convective precipitation that provides the basis for classifying cellular and slabular lines, rather than strictly dynamical similarities. It is envisioned that within both the cellular and the slabular categories, subsets of behavior may be identified on dynamical grounds, but detailed investigation along these lines is beyond the scope of this study.

The rationale for classifying squall lines based on the convective-scale dimensionality extends beyond the scientific interest arising from the striking visual differ-
ences. From a forecasting perspective, the primary weather hazard presented by convective systems is a strong function of the convective-scale organization; for example, the tornado threat is often reduced if convective activity is able to merge into a solid swath (slab). The cellular–slabular distinction is also important for aviation purposes, because air traffic is unable to penetrate a slabular line, but may sometimes pass safely between convective towers in a cellular line. Additionally, the surface rainfall distribution differs substantially between cellular and slabular lines; hence the cellular versus slabular distinction is also of interest to hydrologists and climatologists.

Observations of many convective lines (to be described later) indicate that a spectrum of organizational modes exists between the slabular and cellular extremes. Many linear convective systems exhibit some cellular and some slabular qualities—for example, many squall lines possess continuous along-line precipitation, but still retain substantial inhomogeneities within the convective region (e.g., Kessinger et al. 1987). The primary focus of this paper is to examine the environmental characteristics and system-scale properties that favor the two extremes at the ends of the spectrum.

It should be emphasized that many squall lines do not fall into the continuum of modes bounded by cellular and slabular overturning. Lines composed of short convective segments, arcs, or partially merged cells may occur, as well as systems that lack any discernible organization of the convective elements (e.g., McAnelly and Cotton 1986). It is also important to recognize that a squall line often undergoes an evolution from one class of organization to another. A rather common sequence of events in the central United States is the initiation of a line or cluster of cells in the mid-to late-afternoon hours, followed by upscale evolution to a highly two-dimensional squall line during the evening (Bluestein and Jain 1985). The resulting slabular line may persist for many hours and travel hundreds of kilometers before dissipating. Leary and Houze (1979) document a similar course of events for many tropical convective systems. Evolution from a solid line to a line of discrete cells is less commonly observed.

To the authors’ knowledge, the environmental and system-scale properties that distinguish cell-like and slablike convective lines have not been thoroughly investigated to date. The majority of the conceptual models for squall-line structure and evolution have dealt primarily with the line-normal properties of convective systems, and along-line integrated measures of system strength (e.g., Thorpe et al. 1982; Fovell and Ogura 1989; Garner and Thorpe 1992; Lafore and Moncrieff 1989; Rotunno et al. 1988). Some studies have addressed the degree and development of system-scale three-dimensionality (e.g., Houze et al. 1990; Trier et al. 1998; Weisman and Davis 1998). In contrast, this work focuses on the convective-scale two- or three-dimensionality of linear convective systems. A combination of observational and numerical modeling techniques has been employed to investigate the spectrum of organizational modes ranging from cellular to slabular.

Section 2 describes the observational methods that were used to investigate the typical environmental conditions that favor cellular and slabular squall lines; the results appear in section 3a. The insight obtained from the observations was then applied in numerical experiments using a high-resolution compressible cloud model. The goal of the numerical experimentation was to examine the sensitivity of simulated squall lines to the primary differences observed in the environmental conditions, and to investigate the mechanisms responsible for producing contrasting convective-scale organization. The modeling techniques and results are described in section 3b. Some further aspects of the problem and additional modeling results are discussed in section 4, followed by concluding remarks in section 5.

2. Observational methods

The identification of well-defined examples of slabular and cellular modes of organization was achieved using the WSI product NOWrad composite radar imagery. Composite soundings of the inflow environments of the best examples of both organizational modes were constructed using proximity radiosonde data (details of this technique will be presented below). This approach, wherein soundings considered “representative” of the convective environment are composited for a set of events with common features, has often been employed in studies of convective phenomena (e.g., Bluestein et al. 1987; Rasmussen and Blanchard 1998; Evans and Doswell 2001). Care is needed in the compositing process, both to ensure that soundings are representative, and to prevent the loss of significant features as a result of the averaging (Brown 1993). Both of these aspects are discussed in more detail below.

The selection of cases for the compositing study was based upon the appearance of mesoscale convective systems in the NOWrad composite radar imagery over the continental United States between October 2001 and September 2002. An event was classified as a slabular system if the convective region exhibited an unbroken swath of reflectivity above 40 dBZ, whose along-line dimension was at least 5 times that of the cross-line dimension. Additionally the high-reflectivity
region was required to be at least 100 km in length. These criteria must have been satisfied for at least 1 h continuously.

A cellular line was required to exhibit at least three cells arranged in a linear manner, with peak reflectivities greater than 40 dBZ, for at least 1 h. No rigid size or spacing constraints were imposed for the cells, and individual cells were not required to be long-lived. Between the cells, it was required that the reflectivity fall at least 20 dBZ from the peak value in the cell cores. Some lines that were classified as cellular contained weak precipitation between the cells, while in other cellular cases the cells were discrete and separated by echo-free regions. It was also required that no observable tendency toward a more slablike structure be evident. It should be noted that the radar data provided no direct information about the spatial distribution of vertical velocities within the convective systems. There is no guarantee, therefore, that the systems with a cellular appearance on radar did not contain layer lifting, or vice versa. However, the selection of only well-defined examples of each mode, and the association of high reflectivities with deep ascent and precipitation production, leads to reasonable confidence that truly cellular and truly slabular modes were identified using radar imagery alone.

For each event, the reports from the synoptic radiosonde network were examined to determine whether a sounding was available within a representative inflow environment. As noted by Coniglio et al. (2004), proximity soundings represent the best source of simultaneous wind and thermodynamic data, despite problematic questions about representativeness (Brooks et al. 1994). In this study, the possibility exists that some of the soundings were modified by the preexisting convection, but it was not possible to recognize when this may or may not have happened. Consequently, any sounding that was released ahead of the line and within 150 km of the line’s leading edge at the time of release was examined. The sounding was discarded if wind or thermodynamic data were missing through a layer thicker than 1600 m below 250 hPa, or if a temperature inversion was evident in the lowest 100 hPa. Soundings with surface-based stable layers were regarded as representing an environment conducive to elevated convection, which was not of interest in this study. (It is noteworthy, however, that some elevated convective systems resemble slablike convective lines, and these events should be investigated in future work.) No constraint was placed on the smallest permissible distance between the sounding release site and the convective line; the closest instance used in the compositing procedure was a distance of 34 km.

To explore the two ends of the organizational spectrum described in section 1, the 10 most cellular and 10 most slabular cases were chosen from the set of convective events. The selection of cases was based solely on their appearance in the radar imagery. A “highly” slabular event was one for which the reflectivities were continuous and very homogeneous above 50–55 dBZ; a “highly” cellular case consisted of strikingly discrete, intense (>55 dBZ) cells. For these most distinctly cellular and slabular subsets, the soundings were then composited following the methodology of Brown (1993), which emphasizes the preservation of significant features in the averaging process. The only notable thermodynamic feature that was common to most of the soundings was a surface-based mixed layer; consequently the top of the mixed layer was taken as a significant feature to be preserved in each composite. In practice this meant that values of temperature, dewpoint, and height above ground were averaged at the same proportional distances between the ground and the mixed-layer top. Above the mixed layer, averages were computed at common distances above the mixed-layer top. In two slabular cases, no mixed layer was evident, and in these instances the top of the mixed layer was taken at the ground for the purpose of composing. The kinematic features that were identified and preserved in the slab composite wind profile were low-level maxima in both the line-parallel and line-perpendicular components of the wind. The wind profiles for the cellular cases did not contain any identifiable common features.

3. Results

a. Composite analysis

The composite temperature and moisture profiles of the inflow environments of the top 10 cellular and slabular events are shown in Fig. 3. Both environments exhibit conditional instability, though the values of CAPE are not large. Only 1007 J kg\(^{-1}\) of CAPE is found in the slab environment; this is about 500 J kg\(^{-1}\) less than for the cell composite, though the large variability in CAPE from case to case dictates that this difference is not statistically significant.\(^1\) A more striking difference is found in the depth of the surface-based

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\(^1\) The CAPE of both composite soundings is approximately 350 J kg\(^{-1}\) lower than the mean CAPE of the individual soundings in the respective environments. This difference is considered to be a shortcoming of the compositing technique, but the relative magnitude of the CAPE values is preserved (about 500 J kg\(^{-1}\) greater for cells).
mixed layer, in that the mixed layer is much deeper, and the lifting condensation level is almost 100 hPa higher, in the cell composite. The surface relative humidity is only 50% for the cell cases, compared to about 75% for the slab environment. The difference in mixed-layer depth is significant at the 99% level. All of these differences may be partially explained by the tendency for some slab cases to be observed in the early-morning hours (around 1200 UTC), whereas every one of the cell cases was observed in the early evening (around...
0000 UTC). However, the relatively weak CAPE and high relative humidity of the slab composite is also present in most of the 0000 UTC slab soundings, suggesting that the observed differences are not simply a result of diurnal fluctuations.

Another notable difference in the thermodynamic environments is evident in the vertical distribution of moisture. Slab environments tend to have moister low to midlevels (up to about 500 hPa) and a more pronounced dry layer between 500 and 300 hPa. By contrast, the cell composite shows a gradual drying trend with altitude, up to about 400 hPa. The difference in the density-weighted mean relative humidity in the layer between the top of the mixed layer and 500 hPa is significant to the 95% level. A possible explanation for the reduced mixed-layer depth and higher relative humidity in the slab environments may be that some slabular lines occur in conjunction with strong dynamic forcing from the mid- or upper levels. Externally imposed deep-layer lifting would tend to moisten and cool the environment over a wide area, and may aid in both the initiation and the maintenance of the convective system (e.g., Dudhia and Moncrieff 1987). The upper-level forcing was not investigated for all of the observed systems; however, strong forcing was not a necessary condition for slabular convection, because a number of slabular lines formed in the absence of notable preexisting baroclinicity.

The differences in the kinematic environments of cellular and slabular squall lines are more pronounced than the thermodynamic differences. Figure 4a shows that both environments contain low-level shear directed in the opposite sense to the vorticity generated by the cold pool. The low-level shear is clearly much stronger in the slab composite profile. However, the layer over which the value of the low-level shear should be computed is not immediately obvious. A pronounced low-level maximum of line-perpendicular wind is present at an altitude of 460 m above ground in the slab composite (375 m in the cell composite); in the slab profile, this low-level maximum was used as a common feature with respect to which the composite was constructed (see section 2). Below the level of maximum wind, the wind speed drops off rapidly under the influence of friction. It is therefore apparent that the computation of the low-level shear depends strongly on the level that is chosen for the bottom of the low-level shear layer. Observational studies such as Coniglio and Stensrud (2001) and Evans and Doswell (2001) compute low-level shear using the surface winds. If this methodology is followed, the composite profiles indicate an average 0–2.5 km shear of 7 m s⁻¹ in the slab environments, and 4 m s⁻¹ in the cell environments.

These values are quite consistent with the results of Gale et al. (2002) for long-lived mesoscale convective systems, and are somewhat less than the median values reported for derecho-producing systems by Evans and Doswell (2001).

It is interesting to note, however, that the reduction in wind speed in the shallow near-surface layer is attributable to surface friction, which is not represented in most idealized modeling studies (a free-slip lower boundary condition is typically used, as in this work). It may therefore be inconsistent to use the heavily damped surface wind value in the computation of the low-level shear, if the objective is to perform a comparison to modeling results. The value of the line-perpendicular shear in the 2.5-km-deep layer above the

**Fig. 4.** Wind profiles from the composite soundings: (a) cross-line component and (b) along-line component.
low-level maximum is 14 m s\(^{-1}\) in the slab composite and 5 m s\(^{-1}\) for the cell cases. The former value is close to the low-level shear that is considered optimal for the existence of strong, long-lived squall lines in the simulations of Weisman et al. (1988). Clearly, the measurement of low-level shear from observations is rather sensitive to whether or not the surface-based frictional layer is included. Further investigation of this problem is warranted in light of recent discussion concerning the apparent disagreement between observations and modeling results (Coniglio et al. 2004; Weisman and Rotunno 2004).

Above the low-level shear layer, moderate shear of the same sign extends up to 12 km in both the cell and slab composites, with the exception of a weak-shear layer between 3 and 5 km in the slab environment. The mean 0–6-km shear is 12 m s\(^{-1}\) (6 m s\(^{-1}\)) for the slab (cell) cases, or 17 m s\(^{-1}\) (7 m s\(^{-1}\)) if the bottom of the shear layer is taken at the level of the low-level wind maximum.

In a reference frame moving with the leading edge of the convective line (defined by the center of the line of high-reflectivity features indicating the convective region), the contrast between the line-perpendicular wind profiles is accentuated (Fig. 5). Slabular squall lines experience very strong line-relative inflow, 24 m s\(^{-1}\) on average, at low levels. The inflow to cellular lines, on the other hand, peaks at only 10 m s\(^{-1}\) at low levels. The difference in line-relative inflow speeds is significant at the 99.9% level. Consequently it may be inferred that overturning of a slablike nature ingests low-level potentially buoyant air at a much greater rate than does a typical line of cells. A significant fraction of the difference in line-relative inflow speeds arises from the different rates of movement of lines of cells and slabs. The mean ground-relative speed of the slabular lines (14.2 m s\(^{-1}\)) was much higher than for the cellular lines (6.0 m s\(^{-1}\)); up to a third of this difference is attributable to the difference in mean line-perpendicular wind speeds (Fig. 4a). The difference in line movement speeds is also significant at the 99.9% level.

The two line-parallel wind profiles also differ substantially (Fig. 4b). Most notably, much stronger along-line winds throughout the troposphere are observed in conjunction with slabular squall lines. Strong shear up to about 1 km above ground level is observed in the slab composite, with weaker shear up to 5 km. The cell profile shows moderate shear up to 10 km.

Taken together, the along-line and across-line wind profiles indicate that the slab environment typically exhibits a low-level jet. The concurrence of mesoscale convective systems with low-level jets has been previously documented (Maddox 1983; Laing and Fritsch 2000). The jet provides a large rate of transport of moist, potentially buoyant air to the convective system and often allows vigorous convective overturning to persist into and throughout the night, even while the near-surface temperature drops and surface-based CAPE decreases.

b. Numerical experiments

1) NUMERICAL MODEL DESCRIPTION

The compressible model described by Bryan and Fritsch (2002) and Bryan (2002) was used to investigate the convective-scale evolution of squall lines. Simulations were performed with a horizontal grid spacing of 500 m, and a vertical grid spacing of 200 m below an altitude of 5 km, increasing to 500 m above 8.5 km. Bryan et al. (2003) argued that grid spacings on the order of 100 m or less are required in order for the turbulence closures used in modern cloud models to be appropriate. Simulations with grid spacings of 1 km are unable to resolve an inertial subrange and contain an unacceptably high ratio of subgrid turbulence kinetic energy (TKE) to total TKE. These concerns will apply to some degree to 500-m simulations, and it is acknowledged that higher-resolution simulations may be needed to verify some of the conclusions arising from this work. Nevertheless, relatively coarse grid spacing was chosen for our initial investigations because the requisite large domain (450 km by 90 km) and integration lengths (3–5 h) taxed the available computer resources. Ice microphysics was incorporated in all simulations, adding further to the computational cost. Fi-
nally, we desired to explore the parameter space of kinematic and thermodynamic parameters to some extent, and therefore a significant number of simulations were required. Future investigation will focus on fewer but higher-resolution simulations to test the ideas arising from these preliminary calculations.

The depth of the model domain was 20 km, and a Rayleigh damping layer was applied within the upper 4 km in order to diminish the reflection of gravity waves from the domain top. Periodic lateral boundary conditions were used on the north and south edges of the model domain to allow the squall line to extend across the entire domain. Along the east and west boundaries, open-radiative boundary conditions were used. A free-slip boundary condition was specified along the flat lower boundary. The microphysical model that was used followed Lin et al. (1983), with modifications by the Goddard cumulus ensemble modeling group (Braun and Tao 2000). Five species of water condensate were represented: cloud water, rain, cloud ice, snow, and hail. Because of the fairly short duration of the model integrations, the Coriolis force was not considered. Additionally, no surface fluxes or radiative heating was included.

Squall lines were initialized in the model by introducing a line of warm, moist bubbles stretching across the short dimension of the domain. Each bubble consisted of a potential temperature perturbation of 3 K and a relative humidity of 95% at its center; these perturbations from the base state diminished to zero at a horizontal (vertical) radius of 5 km (2 km). The bubbles were spaced 15 km (40 km) apart along the line of initialization for the slabular (cellular) simulations [see section 3b(2)].

To investigate the effect of varying environmental conditions on the modeled convective systems, several different base states were employed. All base states were horizontally homogeneous, however. The primary temperature and moisture profiles were similar to those used by Weisman and Klemp (1982) and are shown in Fig. 6. Differences from the profiles of Weisman and Klemp (1982) were introduced in order to allow a change in the tropopause height to affect the potential buoyant energy (CAPE) of the sounding. This was required because an alternative sounding was created with a much deeper mixed-layer depth (Fig. 7a), yet with the same wet-bulb potential temperature throughout the mixed layer as in the original sounding, and with essentially the same CAPE. A fourth sounding was created with dry mid- and upper levels (Fig. 7b). McCaul and Cohen (2002) also investigated the effects of modifying sounding parameters while maintaining CAPE, but their study focused on the characteristics of isolated cells.

The various wind profiles used to initialize the simulations are depicted in Figs. 8 and 9. Both across-line (Figs. 8, 9a) and along-line (Fig. 9b) variations in the wind profile were investigated, because the observed composite wind profiles exhibited substantial differences between cellular and slabular environments for both wind components (Figs. 4a,b).

2) CELLULAR LINES

Preliminary testing with the numerical model indicated that simulations initialized with a line of bubbles at 15-km spacing invariably produce a continuous surface-based cold outflow and approximately line-parallel gust front, because the cold pools produced by each cell tend to merge rapidly. By 2 h into the integration, the interaction of the cold pool with the ambient low-level shear produces more or less continuous along-line “layer lifting” at low levels. This sequence of events is common to simulations initialized with a wide variety of wind profiles; even when the wind profile favors discrete supercells to begin with, the close spacing of the cells dictates that a squall line with continuous along-line precipitation is formed within 2 h. Bluestein and Weisman (2000) showed that even with an initial cell spacing of 30 km, numerically simulated, linearly organized supercells interact strongly with each other along a continuous outflow boundary by 2 h, although some orientations of the shear vector are more favorable to maintaining the identity of rotating updrafts.

As a result of the strong tendency of the convectively generated cold pools to merge, it was difficult at first to produce a simulated squall line that exhibited a distinctly cellular mode using the cellular composite (or any other) wind profile. Success was achieved only when a moderate amount of convective inhibition (CIN) was included in a sounding with fairly low CAPE (Fig. 6a), and when the initial cell spacing was increased to 40 km or more. A larger cell spacing increases the time that it takes for the cold pools to merge; decreased CAPE tends to reduce the rate of cold-air production and the cold-pool strength; and nonzero convective inhibition decreases the likelihood that new convection will be triggered along outflow boundaries. All of these characteristics of the initialization tend to work against the “filling in” of the convective line, so that a discretely cellular mode remains for as long as possible. Figure 10 shows the surface cold pool and simulated radar reflectivity at 3 h in a simulation using a wind profile similar to the cellular composite wind profile (i.e., containing moderate shear in both the cross-line and along-line directions; Fig. 4). The convective system consists of a
line of discrete and largely noninteracting supercells. As is to be expected, the removal of the convective inhibition in a different simulation allowed convective overturning to break out at locations between the initial cells, leading to a more continuous squall line structure (Fig. 11). Decreasing the cell spacing and/or increasing the CAPE had much the same effect, although details of the convective evolution differed substantially (not shown).

One of the major differences in the composite wind
profiles was the greater magnitude of the along-line wind component in the slabular environments. Rasmus- sen and Blanchard (1998) stated that “deep tropo-
spheric flow that is largely parallel to low-level ‘trigger’ mechanisms is known to result in solid lines of convec-
tion instead of isolated cells”; this rule of thumb is sometimes employed by Storm Prediction Center (SPC) forecasters (E. N. Rasmussen 2002, personal communication). However, in the idealized modeling framework with its free-slip lower boundary condition,
a uniform increase in the component of the wind in any
direction has no effect on the simulation except via
insignificant numerical effects. The sensitivity to the
along-line shear was therefore tested by increasing the
along-line shear (CELL40 in Fig. 9b). Under the influence of stronger along-
line shear, a continuous surface gust front and continuous along-line precipitation are
obtained more rapidly (Fig. 12). The increased line-
parallel shear implies significant along-line accelera-
tions of updraft air parcels and stronger along-line
transport of hydrometeors aloft. As a result, hydrom-
eteor fallout and cold downdraft production occur at
locations between the initial cells, and the merging of
the low-level cold pools is accelerated. Strong along-
line wind shear is therefore detrimental to the distinctly
cellular mode, as expected. It should be noted, how-
ever, that moderate along-line wind shear seems to be
necessary to maintain discrete cells. As shown by
Bluestein and Weisman (2000) and confirmed in our
experimentation (not shown), wind shear that is near
perpendicular to the line produces a relatively solid
convective system, as cells split and quickly interact
with their neighbors.

In summary, the environmental characteristics that
numerical modeling experiments indicate are favorable
to a distinctly cellular mode of squall-line convection
include a moderate quantity of convective inhibition,
and a deep-layer wind shear vector that is oriented at
an angle of about 60° to the line. A strong sensitivity to
the precise mode of initiation (i.e., the spacing of the
initial cells) is another aspect of the problem. It will be
noted that the composite thermodynamic sounding for
the cellular cases contained only small convective inhi-
bition (6 J kg\(^{-1}\); Fig. 3a). This low value may be an
artifact of the imperfect compositing process, however,
because the mean value of CIN for the top 10 cellular
cases is 23.2 J kg\(^{-1}\) (although 5 of the 10 have zero
CIN). It is also possible that in some of the observed
cases, the CIN exhibited by the sounding was not rep-
resentative of the broader convective environment as a
result of local inhomogeneities (e.g., localized lifting).

3) SLABULAR LINES

As previously discussed, the generation of “layer lift-
ing” at the leading edge of a surface-based cold pool
was almost always observed in less than 2 h after model
initialization, unless the cell spacing was large and the
environment was particularly favorable for the cellular
mode. The majority of simulated squall lines, therefore,
exhibited a slabular mode of overturning at low levels,
although the manner of organization at higher eleva-
tions was extremely variable. Consequently, the nu-
merical investigation of the slabular mode focused on
the depth and strength of the layer lifting, in order to
assess the environmental and system-scale conditions
that favor a high degree of slabular organization.

One of the primary distinctions between the ob-
served environments of slabular and cellular squall
lines is the magnitude of the line-perpendicular line-
relative inflow. As described in section 3a, the line-
relative low-level inflow is substantially greater for slab
cases than for cellular lines, and a major contribution to
the different inflow magnitudes is from the contrasting
rates of movement of cellular and slabular systems. Ig-
noring cases involving elevated convection, the forward
speed of a slablike convective line is typically governed
by the rate of advance of the surface-based cold pool,
because the regeneration of active leading-edge con-
vection usually occurs above the gust front. The speed
of advance of the cold outflow relative to the low-level
inflow is, in turn, controlled largely by the strength and
depth of the cold pool. The hypothesis was therefore
investigated that the existence of a deep, strong cold
pool is particularly favorable to two-dimensional orga-
nization and the generation of intense slabular ascent.
The remainder of this section will show that the nu-
merically modeled squall lines clearly demonstrated the
viability of this hypothesis.

To produce squall-line systems with strong convec-
tively generated cold pools, the slabular composite
thermodynamic sounding was not used, but rather ide-
alized soundings with substantially greater CAPE (Figs.
Additionally, it was not found to be necessary to include along-line wind shear in order to simulate slab-like convection, and consequently all of the slabular sensitivity experiments were initialized with zero along-line winds. An investigation of the effects of variable along-line winds on slabular lines is deferred to a later study.

Many of the mesoscale characteristics of the simu-

![Fig. 9. Wind profiles used to initialize cell simulations: (a) cross-line component and (b) along-line component.](image1)

![Fig. 10. Potential temperature perturbation of $-3$ K (dotted line) and simulated radar reflectivity (dBZ, shaded) at the lowest model level, at 3 h in the simulation with sounding INHIB and wind profile CELL20, and 40-km bubble spacing. Tick marks indicate 20-km distances.](image2)

![Fig. 11. Potential temperature perturbation of $-3$ K (dotted line) and simulated radar reflectivity (dBZ, shaded) at the lowest model level, at 3 h in the simulation with sounding INHIB modified to remove all CIN, wind profile CELL20, and 40-km bubble spacing. Tick marks indicate 20-km distances.](image3)
lated slabular squall lines are similar to previously reported results in the literature and may be illustrated with the simulation using the “RKW-optimal” line-perpendicular wind profile (“RKW” in Fig. 8). A line of vigorous upright convection quickly forms from the line of bubbles, and an anvil of ice hydrometeors spreads out aloft in both the upshear and downshear directions (where the direction refers to the low-level shear). A surface-based cold pool forms, and as the cold pool strengthens, the distribution of hydrometeors aloft becomes biased in the upshear direction. By 5 h into the model integration, a stratiform region of cloud and precipitation has formed upshear of the gust front (Fig. 13).

The characteristics of the convective overturning in the RKW simulation may be described as modestly slabular; that is, the layer lifting is of moderate strength and depth. The vertical velocity field at 2.5 km above ground level is shown in Fig. 14, illustrating that at this altitude the ascent is largely two-dimensional and that individual cells of isolated intense ascent are only just beginning to appear. The swath of ascent is virtually continuous along the line at values up to 8 m s\(^{-1}\). This unbroken slab of ascent is reflected in the equivalent potential temperature (\(\theta_e\)) field (Fig. 15), which also shows a swath of high-\(\theta_e\) air that has ascended virtually undiluted from the surface-based mixed layer. The lowest-level simulated radar reflectivity is shown in Fig. 16 and depicts a continuous swath of reflectivity above 40 dBZ. Some cellular structure is evident at the 50–60-dBZ level.

The use of different line-perpendicular wind profiles leads to substantially different evolutions in the simulated squall lines, as expected. The dependence of the line-perpendicular squall line structure and evolution on the wind shear profile occurs in a manner that is consistent with past results in the literature (e.g., Weisman et al. 1988; Lafore and Moncrieff 1989; Weisman and Rotunno 2004); in general, weaker line-perpendicular shear allows the system to tilt more rapidly upshear, while stronger shear causes the system to remain...
upright or even to acquire a downshear tilt. In support of the hypothesis concerning the role of the convectively generated cold pool, the simulations reveal that the magnitude of slablike ascent is closely related to the strength of the cold pool. When the low-level shear is weak, or when strong reverse shear is included above the low-level shear layer, the cold-pool strength and the overall strength of the convective system are significantly diminished. The system rapidly tilts upshear and precipitation occurs in a more disorganized and weaker manner (e.g., Fig. 17). Two-dimensional ascent along the leading edge occurs up to only 1–2 km above ground level. On the other hand, very strong low-level shear, or strong shear that extends over a deep layer, produces a line wherein continuous along-line low-level ascent breaks down at relatively low elevation (sometimes <1 km) into highly three-dimensional features that may include embedded supercells (Rotunno et al. 1988; Weisman et al. 1988). In these instances precipitation eventually falls into the inflowing air downshear of the convection, and the squall lines resemble the simulated front-fed leading stratiform systems of Parker and Johnson (2004a,c). The cold pool is weak in these convective systems. Both very strong and very weak shear, then, seem to be unfavorable to deep, strong slabular ascent, although the dynamics of the resulting convective systems are very different.

It is of interest to note that using the line-perpendicular wind profile obtained from the slabular composite sounding (Fig. 4a) leads to a squall line consisting of embedded supercell-type updrafts; the anvil aloft is produced exclusively downshear. The line resembles the squall line obtained by Bluestein and Weisman (2000) with deep, strong shear oriented perpendicular to the line of forcing. It is likely that the slabular composite wind profile does not lead to a distinctly slabular squall line in the model (as might superficially be expected) because the upper-level winds observed in the slab cases were influenced by the anvil-level outflow from the existing squall lines. It is well known (Barnes and Sieckman 1984; Lafore and Moncrieff 1989; Weisman et al. 1998) that convective storms may exert a substantial influence on the winds in their proximity; this is illustrated in our simulations by showing the line-perpendicular wind profile 100 km ahead of the
gust front for the RKW simulation (Fig. 18). The deep shear in the profile is greatly enhanced over the initial shear; initializing a simulation with this modified profile produces a squall line with a downshear tilt, similar to that obtained from the slab wind composite (not shown).

The effects of dry air aloft and of increased mixed-layer depth were investigated by performing simulations with the altered thermodynamic profiles shown in Fig. 7; in both of these simulations, the RKW wind profile was used. The lack of moisture at mid- and upper levels (sounding “HIDRY”) caused a weakening of the modeled squall line, presumably owing to increased entrainment into the convective cells. The cold pool was weaker and slab lifting was diminished at the leading edge. A markedly different effect was obtained with drier conditions at low levels (sounding “DEEP”): the cold pool was substantially stronger under the influence of increased evaporation of rain, and slab lifting was extremely strong.

The evolution of the strength of the surface-based cold pool in several of the squall-line simulations is shown in Fig. 19, along with the ratio $C/\Delta U$ defined in Weisman (1992), representing the balance between the cold-pool strength and the low-level shear. As in Weisman (1992), the parameter $C$ was calculated by integrating the negative buoyancy through the depth of the cold pool within 10 km of the cold-pool edge:

$$C^2 = -2g \int_0^H \left( \frac{\theta_p - \theta_{\omega\omega}}{\theta_{\omega\omega}} \right) dz,$$

where $H$ is the depth of the cold pool and $\theta_{\omega\omega}$ is the density potential temperature (Emanuel 1994). The top of the cold pool was defined as the upper limit of the $-1$ K potential temperature perturbation. The low-level shear $\Delta U$ was the 0–2.5-km value used in the base-state wind profile. In most of the simulations the cold-pool strength becomes great enough to dominate the low-level shear by 1.5 h, and the simulated convective systems undergo an evolution toward an increasingly upshear-tilted structure, as reported in many other studies.

To quantitatively compare the nature of the convective overturning with respect to the overall strength of slab lifting in different model runs, a “slab-measuring statistic,” $S$, was devised as follows. First, the vertical
velocity field was translated into a reference frame relative to the gust front position, to obtain a more meaningful along-line average. Then the fraction of grid points along the line at which the vertical velocity exceeded 3 m s$^{-1}$ was calculated for every point in the line-perpendicular cross section. A threshold of 3 m s$^{-1}$ was chosen because it conveniently highlighted the differences between simulations; the same patterns should appear with a different threshold vertical velocity. The slab-measuring statistic $S$ is illustrated in Fig. 20 for the RKW simulation. A swath of locations at which greater than 90% of the grid points along the line are ascending faster than 3 m s$^{-1}$ is evident in the vicinity of the gust front. This swath corresponds approximately to the locations where slabular ascent is taking place. At about 6–8 km above ground, there is a broad secondary maximum in $S$, corresponding approximately to the secondary maximum in along-line averaged vertical velocity (Fig. 21). These secondary maxima reflect the emergence of buoyancy-driven individual cells from the two-dimensional dynamically forced ascent at low levels. In this simulation, the low-level region of high $S$ expands over time as the cold pool strengthens and the dynamically forced lifting above the gust front increases in depth and strength.

The correlation between cold-pool strength and slab lifting within different simulations was quantitatively assessed by constructing an integral measure of the slab-measuring statistic $S$ at half-hour intervals in each simulation. This was achieved by calculating, at each time, the area in the line-perpendicular cross section (e.g., Fig. 20) over which $S > 90\%$. Physically, a larger area of $S > 90\%$ corresponds to more vigorous leading edge lifting, larger vertical mass flux at low levels, and a more intensely slabular system.$^2$ The integrated measure of slab lifting and the integrated cold-pool strength $C^2$ are plotted together in Figs. 22 and 23. Figure 22 shows the results for simulations with low-level shear of 17.5 m s$^{-1}$ over 2.5 km; analogous calculations appear in Fig. 23 for simulations with various low-level shear magnitudes. Clearly, the magnitude of the slab ascent is closely related to the cold-pool strength over a fairly wide range of kinematic and thermodynamic environments. The data points are clus-

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$^2$ A larger area of $S > 90\%$ does not necessarily imply larger low-level vertical parcel displacements; see section 4.
tered around the same slope under quite variable conditions. Figure 23 indicates, however, that the relationship is not independent of the low-level shear; the results suggest that stronger low-level shear reduces the rate of increase of the slab lifting with increasing cold-pool strength.

4. Discussion

The modeling results presented here suggest that the cold-pool characteristics within a linear mesoscale convective system are of fundamental importance for determining the convective-scale mode of overturning. Lines of discrete, noninteracting cells are particularly favored when the cold pools produced by the cells are able to remain separate. An essentially irreversible transition in system structure occurs when isolated cold pools merge together to form a continuous along-line outflow boundary. Thereafter, the inflowing air is constrained to rise in a continuous manner above the gust front, and the convective activity, at least at low levels, takes on a more slabular mode. Moreover, the numerical results show that the intensity of the quasi-two-dimensional lifting in a slabular system is closely related to the cold-pool strength and depth. An important question that arises from these results is whether there is observational evidence that slabular and cellular lines do indeed possess these different cold-pool properties. Unfortunately, surface data were not collected for all the cases included in the observational study, because the focus was primarily on the radar and radiosonde data. Out of the top 10 events in each category, surface observations were available for only 4 slabular events and 7 cellular events. For these cases, the cold-pool temperature deficits were calculated by subtracting the mean air temperature within 50 km behind the squall line’s convective region from a representative surface temperature in the inflow environment ahead of the line. The slabular systems exhibited a mean cold-pool temperature perturbation of 9.9°C, compared to 4.8°C for the cellular cases. The difference is statistically significant at the 99.9% level, but the result should be treated with caution, as the surface observations probably did not adequately sample the spatially confined cold pools associated with the cellular lines. Additionally, no information was obtained about the discreteness or continuousness of the cold pools in the cellular cases. Further observational investigation of cold-pool properties will await a future study.

The suggestion that cold-pool structure and strength is one of the most important parameters in dictating the mode of convective-scale organization of squall lines may appear to be an oversimplification of the complex processes at work in convective systems. Undoubtedly, subsets of squall-line behavior exist that may not be explained in terms of cold-pool processes (Stoelinga et al. 2003). The details of the mid- to upper-level convective overturning, in particular, must depend on many other factors than simply the characteristics of the (relatively shallow) surface-based cold pool. Additionally, many other studies (notably, Thorpe et al. 1982; Rotunno et al. 1988; Weisman and Rotunno 2004) have emphasized the importance of the low-level shear profile in addition to the cold-pool strength for determining the strength of lifting along the leading edge of a convective system.

To elucidate the precise role and importance of the low-level shear in affecting the magnitude of slab lifting (we focus here on slabular systems), the nondimensional experiments of Weisman and Rotunno (2004) were repeated using the cloud model of Bryan and Fritsch (2002). A 1.5-km-deep cold pool with a uniform potential temperature deficit was released in a dry adiabatic environment containing uniform wind shear over the 0–1.5-km layer. The domain was 4 km deep and 48 km wide; the horizontal and vertical grid spacings were 50 m. As in Weisman and Rotunno (2004), a passive tracer was defined such that the tracer value was equal to the elevation of the air parcel at the initial time. By measuring the maximum vertical displacement of an air parcel at the same nondimensional time in each simulation, the results of Weisman and Rotunno (2004) were reproduced. Figure 24 shows the dependence of

**Fig. 23.** Cross-sectional area of slab ascent ($S > 0.9$) and cold-pool strength $C^2$, plotted every 30 min from 1 to 4 or 5 h for five simulations with variable low-level shear. The shear magnitude over the 0–2.5-km layer is indicated by the number following the sounding label (“DEEP” or “SHAL”). The winds were constant above 2.5 km. The best-fit line from Fig. 22 is plotted.
the maximum parcel displacement on wind shear and cold-pool strength. The straight line marks the axis along which the shear magnitude and the cold-pool strength are theoretically in balance; the results confirm that the greatest parcel displacements occur when the cold pool and shear are approximately balanced.

However, a different picture of the behavior of the lifting is obtained by calculating the net upward mass flux in the vicinity of the cold pool’s downshear edge at the same nondimensional times. The mass flux was measured at the 1.5 km level (the initial top of the cold pool), and was integrated within a section centered on the main updraft’s maximum vertical velocity. The boundaries of the measurement section were somewhat arbitrarily fixed at 1 km outside the edges of the updraft (occasionally a series of subsidiary updrafts and downdrafts on the downshear side was present; the integration was performed over all the updrafts and downdrafts greater than 0.1 m s\(^{-1}\) in magnitude). Figure 25 depicts the dependence of the net upward mass flux on cold-pool strength and shear. The results indicate that an “optimal” shear magnitude exists for a given cold-pool strength; but for a given shear magnitude, the mass flux increases monotonically with increasing cold-pool strength. Therefore, the maximum displacement and the upward mass flux behave differently with respect to their dependence on cold-pool strength. Based on this simplified model, it appears that greater cold-pool strengths reliably increase the total mass flux at low levels (for a given shear), whereas the behavior of maximum parcel displacements is more complicated.

The nature of strong layer lifting within a slabular convective system clearly includes both large parcel displacements and substantial upward mass fluxes. Consequently, the perceived controls on slabular ascent depend on the measure that is used to determine whether the ascent is relatively “strong” or “weak.” In this paper we choose to emphasize bulk measures of slab lifting, such as the integrated slab measuring statistic (section 3) and the upward mass flux, as viable indicators of the overall intensity of the slab. Both the full-physics simulations and the simplified cold-pool model suggest that these integrated measures of lifting exhibit a near-monotonic dependence on the cold-pool strength (all other parameters being equal). Nevertheless, for a given cold-pool strength, variations in low-level shear certainly have substantial effects (Figs. 23, 25). Moreover, the presence of environmental shear is undoubtedly important for the existence of the long-lived linear system itself and hence for the existence of the cold pool; without shear as an organizing influence, the system would be disorganized and weak at best. This paper does not, therefore, aim to deemphasize the role of shear for the organization and maintenance of squall lines, but rather to focus on the effects of cold-pool properties on convective-scale organization.

The importance of the cold pool in terms of convective-scale organization leads to the question of environmental influences on cold-pool properties. Clearly, both the thermodynamics and the ambient wind profile exert strong, nonlinear influences on the cold-pool shape, strength, and depth. The complexity of the controls and feedbacks, and the fact that the cold-pool properties rarely remain constant over time in any particular event, imply that the prediction of the nature of the cold pool that will be produced in an imminent
convective event is a difficult problem. The inability to accurately predict cold-pool properties is well known among forecasters of severe weather, because the same difficulty arises when attempting to assess the potential for a convective event to satisfy the RKW condition of balance between the cold-pool vorticity and the low-level shear vorticity. Some discussion of the controls on cold-pool evolution, based on our numerical results, is therefore warranted.

The squall-line simulations indicate that the cold-pool strength is highly sensitive to thermodynamic parameters in the environmental sounding. In agreement with other studies (e.g., Weisman 1992), the results show that higher CAPE tends to strengthen the cold pool and hence also the tendency to manifest strong slab lifting. A higher lifting condensation level (a deeper mixed layer) is very favorable for a stronger cold pool in the slab simulations, although presumably an optimal mixed-layer depth exists above which the convection begins to weaken. Dry air aloft was found to be inimical to convection and caused a weakening trend in the slabular lines.

For a given thermodynamic environment, stronger line-perpendicular shear, especially at low levels, tends to generate a stronger cold pool, as the convective mass flux and cold downdraft production are greater. There is, however, a shear magnitude that is optimal for producing a strong cold pool (Weisman and Rotunno 2004). Shear stronger than the optimal value implies that the advancement of the leading edge of the cold air at the ground is impeded relative to the advection of the deep cloud mass aloft. Consequently, cloud and precipitation aloft move ahead of the surface-based cold outflow, so that rain falls into the low-level inflow. In this scenario the cold pool is relatively weak, although the convective system may remain vigorous and long-lived (Parker and Johnson 2004a). If strong midlevel shear is present, the cold pool may also be weakened owing to the inimical effects of the shear on downdraft formation (Weisman and Rotunno 2004).

The optimal shear magnitude to obtain a strong cold pool varies substantially depending on the thermodynamic profile. In simulations with a shallow mixed layer, it was found that the strongest cold pool and best slab lifting were obtained with low-level shear of about 17.5 m s$^{-1}$ over 2.5 km. When a deeper mixed layer was used, further strengthening of the cold pool was observed when the low-level shear was raised to 22.5 m s$^{-1}$ over 2.5 km; higher values of shear were not tested. In general, the optimal shear magnitude is stronger when the thermodynamics or other factors favor a strong cold pool, because a stronger cold pool advances more rapidly and is less easily overtaken by the cloud mass aloft.

A noteworthy aspect of the controls on cold-pool evolution and slabular ascent is the fact that substantially different environmental conditions may give rise to very similar modes of convective organization in terms of the degree of slab lifting. For example, a sounding with a deep mixed layer and weak shear may produce layer lifting that closely resembles that generated in an environment of stronger shear with a shallower mixed layer. This notion is illustrated using the simulation with a deep mixed layer but with low-level shear of only 6.0 m s$^{-1}$ over 2.5 km, and the simulation in a shallow mixed-layer environment with shear of 17.5 m s$^{-1}$. After 3.5 h of integration, the two squall lines had cold-pool strengths of 775 and 833 m$^2$ s$^{-2}$, respectively, and integrated slab areas of 5.0 and 5.1 km$^2$. Other aspects of the simulations differed considerably, but the low-level slab lifting was very similar.

5. Summary and concluding remarks

An observational study of mesoscale convective systems over the continental United States was performed, with the goal of distinguishing between the inflow environments of cellular and slabular convective lines. The classification of lines as cellular or slabular was subjectively performed based upon their appearance in composite radar reflectivity images. The best examples of the two categories, for which suitable radiosonde data were available, were selected to construct composite soundings. The most notable differences between the two composite soundings were observed in the wind profiles. Convective lines exhibiting a cellular mode of organization tend to form in environments with rather weak low-level shear, but with substantial deep shear in both the line-parallel and line-perpendicular directions. Slabular lines, in contrast, typically experience much stronger low-level shear in the cross-line direction, as well as strong shear in the along-line direction. Most notably, the low-level line-relative line-perpendicular inflow of the slab environments is much stronger than that for the cell environments.

A numerical model was used with 500-m horizontal grid spacing to examine the dependence of the mode of convective overturning on environmental conditions. The simulations displayed a strong tendency to produce continuous along-line precipitation, in conjunction with a quasi-linear gust front and low-level layer lifting. Long-lived lines of discrete cells were obtained only with a shear vector oriented at about 60° to the line, in an environment containing moderate convective inhibition, and with convective initiation confined to widely
spaced locations along the line. These conditions allowed the convectively generated cold pools to remain separated for long periods of time. The merging of the cold pools tended to coincide with a transition to a more “solid” mode of convection, characterized by quasi-two-dimensional lifting above the gust front.

Within the subset of slabular simulations, a clear relationship was found between the strength of the leading-edge slab ascent and the integrated strength of the surface-based cold pool. The magnitude of lifting, as measured by an integrated mass-flux-type statistic, was closely related to the strength and depth of the cold pool, and the correlation was surprisingly independent of several kinematic and thermodynamic characteristics of the environment. The near-monotonic dependence of leading-edge lifting on cold-pool strength was confirmed using a simplified model of a cold-pool spreading in shear, similar to Weisman and Rotunno (2004). The well-known “optimization” of lifting under the condition of cold pool–shear balance was also reproduced, but was found to apply specifically to maximum parcel displacements and not to integrated measures of lifting such as mass flux.

The correlation of cold-pool strength to slabular convection as outlined in this paper does not diminish the importance of environmental shear for the maintenance and organization of a convective system. Numerous studies have shown the dynamic importance of shear as an organizing mechanism, although the magnitude of shear that is needed for a strong, long-lived linear system is still under debate. A primary purpose of this paper, however, is to document that the close relationship between slablike lifting and cold-pool strength is affected surprisingly little by varying environmental parameters. The cold-pool strength itself, and of course many other system characteristics, are strongly affected by the shear, but the cold pool–slab relationship appears to be quite robust. Therefore we conclude that in most circumstances, a long-lived linear convective system with a persistently strong cold pool will exhibit a strongly slabular mode of overturning. A weak cold pool, which may be attributable to a large number of thermodynamic and/or kinematic factors, leads to relatively weak ascent above the gust front and a more rapid emergence of three-dimensional features above the dynamically forced lifting at the leading edge of asquall line. The lack of a continuous along-line cold pool altogether, with the convectively generated cold downdrafts confined to discrete locations along the line, causes a discretely cellular mode.

The cloud-scale characteristics of squall-line convection comprise a subject that requires a great deal more study. Besides further observation of the environmental distinctions between slabular and cellular convective systems, it is important that squall lines be simulated at higher resolution in order to gain confidence that the modes of overturning are robustly represented. The mechanics of the cloud-scale processes within the convective region must be closely examined using the high-resolution output. It is possible that convective rolls within the moist absolutely unstable layer (Bryan and Fritsch 2003) are crucially important in determining the spacing of cells that emerge from the low-level swath of forced ascent. The characteristics of the breakdown into isolated cells or plumes may depend on the meso-synoptic-scale environmental conditions via the properties of the convective rolls. Roll-like features were present in a number of the simulations reported here, and their properties and importance warrant further investigation. Ultimately it is imperative that observations are obtained at cloud-scale resolution in order to verify model output and firmly establish a conceptual understanding of the structure and evolution of squall-line convection.

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