Simulated Convective Lines with Parallel Stratiform Precipitation.
Part II: Governing Dynamics and Associated Sensitivities

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ABSTRACT

This article is the second of two describing convective lines with parallel stratiform (PS) precipitation. The PS mode appears to be the preferred organizational structure in environments with line-parallel vertical wind shear. This paper presents a detailed analysis of the processes that lead to the development of the PS structure within line-parallel shear, and the positive and negative feedbacks associated with the mature PS structure. As well, the particular importance of line-perpendicular and line-parallel wind shear, line-end effects, inertial stability, and patterns of convective initiation are investigated through a battery of sensitivity tests.

Convective lines with PS precipitation develop in environments with both significant line-perpendicular and line-parallel vertical wind shear. Although the studied environments are initially supportive of supercells, the merging of outflows soon renders a predominant linear forcing and the characteristic PS structure. The systems’ linearity in the presence of along-line wind shear makes the local wind field more dependent upon the mesoscale structure of the convective system. For example, the along-line transport of hydro-meteors is required for the development of a line-parallel precipitation region, and yet this transport does not occur immediately down the convective line’s axis because it is interrupted by the pressure maxima associated with other convective cells that are farther down the line. However, the along-line flow within the line’s leading and trailing anvils is able to contribute substantially because there are along-line pressure gradient accelerations associated with the tilted mesoscale structure of the system’s buoyancy field.

This paper concludes the study by synthesizing its dynamical and sensitivity analyses with the overarching structures described in the companion article, yielding perhaps the first consolidated view of these little-studied systems.

1. Introduction

As reviewed by Parker (2007, hereafter Part I), different organizational modes of mesoscale convective systems (MCSs) have unique kinematic features and may be associated with different probabilities for various societal hazards. Despite this, the relatively common arrangement of a convective line with parallel stratiform (PS; Parker and Johnson 2000) precipitation, which frequently emerges in environments with significant line-parallel vertical wind shear, has received relatively little study to this point in time. Part I combined a case study and idealized numerical simulations as an introductory exposition of the basic structures of such PS systems.

In Part I, convective lines with PS precipitation were found to develop in environments with a combination of deep line-parallel wind shear and low-level line-perpendicular wind shear. In such situations, lower-tropospheric storm-relative hydrometeor advection and outflow expansion toward the line’s right\(^1\) produces back-building, while upper-tropospheric storm-relative hydrometeor advection toward the line’s left produces a line-parallel precipitation region. These behaviors together combine to give rise to the characteristic PS structure. However, the along-line flow down the axis of the simulated convective lines is considerably weaker

\(^1\)As in Part I, where left and right appear in this paper, they have a meaning consistent with that of Byers and Braham (1949), that is, to the left and right as one peers down the line’s motion vector. This designation is also equivalent to one’s left and right when looking outward from the convective line toward the line’s inflow-facing side.
than that of its surroundings. Therefore, much of the along-line transport of hydrometeors was found to occur in the nearby line-leading and line-trailing anvil, rather than along the axis of the convective cores.

Because the along-line hydrometeor transports accomplished by convection-processed air are crucial to the formation of a PS system, the dynamics that result in the along-line velocities of these air parcels are of prime interest. These governing dynamics, and the associated sensitivities of the simulations to the base-state environment and the numerical model’s configuration, are the concerns of the present article.

Section 2 of this paper introduces methods that are new or different from those introduced in Part I. Thereafter, section 3 discusses the dynamics governing air parcel accelerations in a representative updraft during the simulated PS system’s developing stages. Section 4 then presents the results from experiments testing the sensitivity of the simulations to the vertical wind shear, the three-dimensionality of the numerical model, the inclusion of the Coriolis acceleration, and the method of convective initiation. Section 5 wraps up the study by retracing the results from Part I and Part II and presenting a synthesized view of convective lines with PS precipitation. Finally, the paper concludes with some possible directions for future work and a brief summary.

2. Methods

a. Numerical model

The basic configuration of the Advanced Regional Prediction System (ARPS; Xue et al. 2000, 2001) for this study was described in Part I. As in Part I, the model was configured such that $y$ was the along-line coordinate, and $x$ was the across-line coordinate. In addition to the control and compartmentalized shear (CS) simulations described in Part I, a battery of sensitivity tests involved alternately increasing and decreasing the values for the line-perpendicular ($u$) and line-parallel ($v$) shear by 50% in the CS profile (CS-1.5xUs, CS-0.5xUs, CS-1.5xVs, CS-0.5xVs; Fig. 1), in order to test the importance of each component. As well, in order to test the importance of line-end effects upon the simulated PS systems, the aforementioned shear experiments were also performed on a y-periodic, quasi-2D (Q2D) domain that was 200 km long in the along-line ($y$) direction. The Q2D matrix of sensitivity tests was also performed for the control wind profile (control-1.5xUs, control-0.5xUs, control-1.5xVs, control-0.5xVs; Fig. 1); this was possible for the control simulations in the Q2D framework because the convective line was not able to reorient itself as it did in the fully 3D simulations (e.g., Fig. 12 of Part I). Additional modifications of the experimental design for sensitivity tests are explained as they arise in the text.

\[ \text{Fig. 1. Wind profiles utilized in the numerical experiments. (a) Line-perpendicular winds ($u$, m s}^{-1}). (b) Line-parallel winds ($v$, m s}^{-1}). \text{The thick curves are variations on the control wind profile, based on four archetypal PS MCSs (see Part I). The thin curves are variations on the CS wind profile (see Part I). The long-dashed curves represent experiments in which the magnitude of the vertical wind shear was increased by 50%, whereas the short-dashed curves represent experiments in which the vertical shear was decreased by 50%. Thus, e.g., the CS-1.5xUs experiment used a wind profile given by the thin, long-dashed curve in (a).} \]
b. Dynamical analysis framework

Because the background total water content in the middle and upper troposphere is quite low, air parcels with higher water content from the convective line are required for significant line-parallel stratiform precipitation to develop. In this regard, horizontal accelerations in the updraft region are of prime importance. Therefore, the perturbation pressure field was analyzed as in Parker and Johnson (2004a,c). The anelastic part of the pressure field can be diagnosed using the method presented by Williamson and Ogura (1972). Following Rotunno and Klemp (1982), separation of the pressure perturbation into buoyant and dynamic parts,

$$p' = p'_B + p'_D,$$  \hspace{1cm} (1)

yields the following relationships in the anelastic system:

$$\nabla^2 p'_B = \frac{\partial}{\partial z} \left( \rho_o B \right);$$  \hspace{1cm} (2)

$$\nabla^2 p'_D = -\rho_o \left[ \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 + \left( \frac{\partial w}{\partial z} \right)^2 \right] - 2\rho_o \left( \frac{\partial u}{\partial z} \frac{\partial p}{\partial y} + \frac{\partial v}{\partial z} \frac{\partial p}{\partial x} + \frac{\partial w}{\partial z} \frac{\partial p}{\partial y} \right),$$  \hspace{1cm} (3)

wherein \( B \) is the buoyancy and all other variables have their conventional meanings; the terms in (3) are labeled following Klemp (1987).

Atmospheric phenomena can be coarsely categorized as either fast-manifold acoustic wave processes or slow-manifold processes, which are presumed to be more meteorologically significant. The anelastic pressure Eqs. (2)–(3) describe the pressure field governing the slow-manifold processes, assuming that the acoustic waves adjust the pressure field at infinite speed. The ARPS model is fully compressible, so in this study the total \( p' \) field is used in the decomposition, with iterative relaxation of \( p'_B \) and \( p'_D \) being constrained by (1). This decomposition may seem needless in a fully compressible model. However, it is insightful because the total pressure gradient, which accelerates the flow, can then be associated with unique, recognizable physical processes.

Parker and Johnson (2004a) described some simple cold pool, updraft, and wind shear configurations that are associated with components of the perturbed pressure field in linear3 convective systems. Without repeating their discussion, for the purposes of the following analyses it is most notable that \( p'_B \) is minimized (maximized) beneath regions of positive (negative) buoyancy; \( p'_D \) is maximized in regions of convergence or deformation, such as on the upshear side of an updraft in vertical wind shear, and is minimized in regions of horizontal or vertical vorticity, including on the downshear side of an updraft in shear.

To make the discussions and labeling simpler, this publication employs abbreviated names for the terms in the decomposed momentum equation, as shown by brackets below. Neglecting compressibility, friction, and planetary rotation as unimportant for convective-scale analysis, the equation for motion is

$$\frac{Du}{Dt} = -\frac{1}{\rho_o} \nabla p'_B - \frac{g}{\rho_o} (\rho'_\text{gas}) - gq_h - \frac{1}{\rho_o} \nabla p'_D,$$  \hspace{1cm} (4)

wherein \( \rho'_\text{gas} \) is the density perturbation attributable to the gaseous constituents and \( q_h \) is the total hydrometeor mixing ratio. The terms ACCB and ACCD are short for the buoyant and dynamic components of the acceleration vector, respectively. The abbreviations in (4) appear throughout this article. It should be clear from (4) that the horizontal and vertical structure of the perturbation pressure field is fundamental to the accelerations experienced by air parcels. For this reason, the remainder of the text describes the physical processes associated with maxima and minima in the \( p' \) field.

3 A linear convective system is one that contains a convective line. This is the sense of linear throughout the text. As used here, the term is not related to the linearization of mathematical equations.

3. Dynamics governing the PS structure

To address the development of the line-parallel precipitation region that attends the PS mode it is necessary to elaborate on the processes that account for the along-line accelerations experienced by air parcels that are ascending in the convective line. The following describes the dynamics governing both the line-perpen-
dicular and line-parallel flow fields in the CS simulation. Although this simulation has the admitted artifice of compartmentalized $u$ and $v$ wind shear, it is instructive because it maintains its orientation with respect to the original wind profile. Therefore, the line-parallel and line-perpendicular components of the acceleration vectors are easy to analyze, and their relationship to the vertical wind shear in each layer is more straightforward.

This section takes the approach of first describing the accelerations experienced by air parcels within a typical updraft during the simulated PS system’s formative stage; this explains why the PS region begins to develop. Thereafter, additional complicating factors within the mature PS structure are presented.

a. Updraft cycle during formative stage

As will be discussed later, the mature PS structure entails several positive and negative feedbacks upon the accelerations imparted to air within the convective region. However, of initial concern is the manner by which the PS structure itself evolves. As outlined in section 2, the preferential development of a line-parallel precipitation region necessitates that inflowing lower-tropospheric air parcels, which have high water content, are processed by the deep convection and exit the convective region with predominantly along-line velocities. Therefore, the line-perpendicular and line-parallel accelerations during the line’s formative stages are of prime interest.

1) LINE-PERPENDICULAR AND LINE-PARALLEL ACCELERATIONS

The present analysis focuses on an individual updraft cycle that extends from roughly $t = 48–67$ min within the CS simulation. By this time, the original linear warm thermal has produced a long cold pool and then multiple subsequent individual cells along its outflow (Fig. 2). By $t = 48$ min the convective updrafts are fully and realistically 3D, are unique from one another, and are qualitatively very similar to the updrafts that occur throughout the following hours. In other words, by this time isolated lifelike updrafts have developed. The following updraft is representative, and it therefore the focus of an investigation of the dynamics that eventually lead to the development of the line-parallel precipitation region.

During the developing stages of the cell ($t = 48–50$ min), an enhanced gust front updraft develops at the leading edge of the system’s cold pool (Fig. 3a). The upward vertical accelerations responsible for the developing updraft are associated with the cold pool’s $p\prime_H^D$ (Figs. 3c,d). The developing updraft is also weakly positively buoyant (Figs. 3a,b) due to latent heat release, which contributes slightly to the positive ACCB.

The $p\prime_D$ field includes a contribution due to the updraft’s presence within low-level line-perpendicular vertical wind shear (recall Fig. 1); this is fairly small in the early going because the updraft is not yet strong. The $p\prime_D$ field also includes the contributions of gust front convergence (maximizing $p\prime_D$) and horizontal vorticity in the cold pool head (minimizing $p\prime_H^D$). The updraft-in-shear contribution implies a pressure maximum on the updraft’s upshear (western) side, which largely offsets the minimized pressure in the cold pool head. This compensation is important, because it diminishes the impact of the cold pool head’s pressure minimum, thereby enabling the air parcels to spend more time in the zone of upward ACCB before they are accelerated away rearward. As these contributions largely offset, the remaining signature is therefore of weakly maximized $p\prime_D$ at the gust front associated with convergence there (Fig. 3e); this maximum entails a weak upward dynamic ACCD. Because there is no line-parallel wind shear in the lowest 3 km of the CS simulation, and because the cold pool head and gust front convergence are more uniform in the along-line direction, there is relatively little line-parallel structure to the $p\prime_D$ field at this stage.

As the net upward accelerations (Fig. 3) continue to act, the lower-tropospheric updraft broadens and intensifies, exceeding 10 m s$^{-1}$ during the period $t = 51–54$ min (Fig. 4). The updraft is increasingly positively buoyant (Figs. 4a,b), and upward ACCB associated
Fig. 3. Mean velocities, perturbation pressures, and acceleration terms for the CS simulation from \( t = 48-50 \) min. (a), (c), (e) Line-perpendicular (\( z \) vs \( x \)) cross sections; (b), (d), (f) line-parallel (\( z \) vs \( y \)) cross sections; (a), (b) BUOY-contoured, and 2D tangential wind vectors; (c), (d) \( p' \)-contoured, and 2D tangential ACCB vectors; (e), (f) \( p''_y \)-contoured, and 2D tangential ACCD vectors. Vertical velocity is shaded in all panels: levels of shading are 5 and 10 m s\(^{-1}\). Contour intervals and vector scales are shown for each panel, and vary among panels. Terms are defined in section 2b. The \( x, y \) point at which the line-perpendicular and line-parallel cross sections intersect is indicated by a thin vertical line.
with the cold pool’s \( p_B \) continues to accelerate inflowing air upward into the updraft (below 2 km in Fig. 4c). Although the flow within the updraft is still largely westward at this time (Fig. 4a), as the updraft grows stronger, the eastward line-perpendicular ACCD also grows stronger due to the updraft-in-shear contribution (Fig. 4e). Thus, as originally emphasized by Rotunno et al. (1988), the presence of low-level line-perpendicular
shear enables the gust front updraft to be more erect and intense in time.

Although the near along-line uniformity of the surface outflow results in a continued uniformity to the line-parallel cross section of $p'_B$ and ACCB (Fig. 4d), by this time the top of the updraft has begun to ascend above 3 km, into the CS layer in which the along-line vertical wind shear exists (recall Fig. 1). Therefore, in concert, $p'_B$ is maximized to the updraft’s south and minimized to its north, entailing a northward along-line ACCD (Fig. 4f). Indeed, in the $t = 51–54$ min window, the inflowing air’s original southward component of motion has been almost completely removed by 5 km AGL (Fig. 4b). In time, this ACCD will produce updraft parcels with northward along-line velocities, a key element in the development of a line-parallel precipitation region.

By the $t = 55–58$ min time window, the updraft is maturing and spans much of the depth of the troposphere. The updraft has significant positive buoyancy (Figs. 5a,b), associated with which is a large upward ACCB (Figs. 5c,d). Reflecting the updraft’s increasing strength, the line-parallel depiction of $p'_B$ and ACCD has much the same structure as during the prior time window, but the magnitudes are yet greater (Fig. 5f). Owing to these downshear accelerations, the updraft has begun to tilt northward in the along-line direction (Fig. 5b), and air parcels near the updraft top now have considerable southerly velocities (Fig. 5b). Along with this, the updraft’s patch of positive buoyancy now also tilts northward with height. The associated $p'_B$ therefore gains some along-line structure, with a slight along-contribution to ACCB (Fig. 5d). However, this is dwarfed by the dynamical contributions to along-line accelerations (cf. Figs. 5d and 5f). As updrafts mature, the along-line ACCD is the chief forcing for the significant along-line northward flow that will eventually promote a PS region in the simulation.

The line-perpendicular presentation of $p'_B$ may be somewhat surprising in appearance (Fig. 5e). In addition to the persisting low-level maximum associated with convergence there is a similar updraft-top maximum associated with the deformation there. There is also a minimum in $p'_B$ on the updraft’s eastern side, which implies a continuing eastward ACCD. As a result of this, the updraft is now almost fully erect in the line-perpendicular cross section. However, the minimized $p'_B$ on the updraft’s eastern side may seem to be incongruous with the lack of line-perpendicular vertical wind shear in the layer. It is related to two effects.

First, there is horizontal vorticity associated with the updraft’s horizontal gradient in $w$, and its magnitude is greatest on the updraft’s eastern side due to the sharp curvature of the flow field on the radially inward flank of an overturning updraft (as discussed by Parker and Johnson 2004a). Second, the pair of vertical cross sections is but an imperfect depiction of a fully 3D updraft. In the presence of deep-layer vertical wind shear, updrafts have long been known (e.g., Klemp and Wilhelmson 1978) to produce flanking, counterrotating vortices due to the tilting of environmental horizontal vorticity. Because these flanking vortices are oriented so as to be normal to the deep layer vertical wind shear vector (which points northeastward), they are not perfectly aligned with either the line-parallel or line-perpendicular axis in the CS simulation (Fig. 6a). Hence, the vertical cross section in Fig. 5e, which is taken along $y = 255.5$ km, intersects a pressure minimum associated with updraft-flanking vorticity on the updraft’s eastern side to a greater degree than on its western side (cf. Figs. 5e, 6b).

2) UPDRAFT SPLITTING AND DEMISE

These updraft-flanking vortices are important during the early stages of the PS system’s development because they can lead to storm splitting (Schlesinger 1980; Rotunno and Klemp 1982, etc.). A reasonable question is whether supercell-like behaviors are observed within PS systems, which occur within highly sheared vertical wind profiles. During the $t = 59–61$ min time window, the storm-splitting process becomes evident in the line-perpendicular vertical velocity field (Fig. 7a). Upward ACCD on the original updraft’s southeastern flank (Figs. 5 and 6) has lead to an emerging secondary maximum in upward motion to its east. The trends in the line-parallel cross section are quite similar to those for the $55–58$-min window (cf. Figs. 5b,d,f and 7b,d,f), and their explanations are the same. The continued along-line accelerations have given rise to a significant northward component in the flow at anvil level by this time (Fig. 7b). In addition, the new updraft development that is occurring to the southeast of the main updraft is also partly evident as the small protrusion of positive $w$ that extends southward from the updraft’s base (Fig. 7b).

As the split is ongoing, the dissipating phase of the old updraft also begins. The updraft has produced a significant amount of precipitation (in excess of 10 g m$^{-3}$), which falls into the inflowing airstream (not shown) and leads to buoyancy reversal. By the $t = 59–61$ min window, the old updraft is no longer positively buoyant.

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1 The observed 2 May 1997 PS MCS (Part I) exhibited similar vortex pairs when a coarse dual-Doppler analysis was constructed (not shown).
below roughly 4 km AGL (Figs. 7a,b), and downward ACCB begins to occur at low levels (Fig. 7c, around $x = 282$ km). Therefore, even though the air farther aloft continues to be positively buoyant, low-level inflowing air no longer ascends into the base of the updraft (cf. Figs. 5a and 7a). This process frequently limits the lifetime of erect or downshear-leaning updrafts, as discussed in more detail by Parker and Johnson.
In some other system updrafts around this time, there is a weak suggestion that the ACCB field helps to detach the maturing updraft from its inflow, as suggested by Fovell and Tan (1998), but this is barely detectable in Figs. 4c, 5c, and 7c. In either case, because the dissipating updraft no longer exists below 3 km AGL (where there is line-perpendicular wind shear), the line-perpendicular $p/D$ and ACCD fields are small again.

By the $t = 62–67$ min time window, the updraft split is nearly complete, and the new updraft (centered in Fig. 8) has supplanted the dissipating original updraft (visible above 5 km at $x = 280$ km in Fig. 8a; above 7 km at $y = 259$ km in Fig. 8b). This newly predominant updraft is mature and now exhibits many of the features exhibited by the original updraft during its mature stage (cf. Figs. 5 and 8), with similar explanations. The new updraft is marginally stronger than its predecessor, but it still leans northward and exhibits southerly flow in its upper reaches (Fig. 8b), as a result of the significant downshear ACCD (Fig. 8f).

During its developing stages, the new updraft was collocated with the preexisting vertical vorticity, such that the flow appeared to be more helical, as in a classical supercell. However, as the updraft matured and strengthened, the center of vertical vorticity quickly moved to its flank due to the production from tilting. Thus, the finding of Bluestein and Weisman (2000) also applies here: within the squall line, updrafts have some supercellular properties, but are not very well correlated with the vertical vorticity. Because the newer updraft also exhibited a flanking vortex pair (not shown), it might ordinarily be primed for additional splitting or redevelopment along its edges. However, in the simulation at hand, the new updraft collided with another cell to its south and did not split again (not shown).

Later in the PS simulations (e.g., after roughly 2 h), the surface cold pool rapidly strengthens (Part I). Such strengthening suppresses the tendency for isolated quasi-supercellular elements and storm splitting. The cold pool’s edge forces a strongly linear gust front updraft, which is therefore less amenable to the development of isolated cells. Some mature updrafts during the later stages of the simulations still exhibit flanking vortices due to tilting of environmental horizontal vorticity. However, these cells are generally well rearward of the surface outflow boundary due to the deep solenoidal circulation associated with the enhanced cold pool. As a result, although upward ACCD occurs along updrafts’ flanks, these accelerations are atop the surface outflow and not properly placed to generate an updraft that will ingest environmental inflow. Therefore, fully realized storm splitting becomes quite rare once a PS system has intensified its cold pool.

b. Mesoscale structure and accelerations

The first part of this section was devoted to explaining how the line-parallel precipitation region originally develops due to along-line accelerations within the convective updrafts. However, as described in Part I, over time the vertical wind shear within the convective region becomes diminished. The mesoscale structure of
the PS system within deep line-parallel wind shear plays an active role in producing this decrease.

Although air parcels that are processed in deep convective updrafts acquire significant along-line accelerations, trajectories reveal that they do not indefinitely move northward down the line’s axis. As an updraft is maturing near \( x = 276 \text{ km}, y = 269 \text{ km} \) (comprising parcels A–C in Fig. 9), air parcels that ascended within

Fig. 7. Same as Fig. 3 except for the CS simulation from \( t = 59–61 \text{ min} \).
earlier updrafts and are moving northward exhibit signs of lateral deflection away from the line’s axis (trajectories D–J in Fig. 9). In some cases, these air parcels leave their updrafts and already possess a significant westward (e.g., parcel I) or eastward (e.g., parcel J) component of motion as they move along the line. However, many of the trajectories at one time or another display a pronounced change in their direction of motion.

Fig. 8. Same as Fig. 3 except for the CS simulation from $t = 62–67$ min.
which is usually away from the line’s axis (e.g., parcels D, E, F). Although it is not possible to show them all, a majority of the trajectories passing through the convective region exhibit this behavior to some degree. Trajectories such as G in Fig. 9, which move along the line’s axis for longer periods, are relatively rare.

The dynamic pressure perturbation tied to the downshear along-line accelerations (e.g., Fig. 5f at $y = 254.5$ km) experienced by updraft parcels also simultaneously implies maximized $p_{D}'$ on the upshear side of the next updraft along the line. As well, updraft-top convergence implies an additional positive contribution to $p_{D}'$ along the line’s axis in the upper troposphere (e.g., Fig. 5e at $z = 7.5$ km; Fig. 7e at $z = 11$ km). On the whole, these effects entail maximized $p_{D}'$ along much of the convective line in the middle and upper troposphere (shading in Fig. 10b). The simulated within-line pressure maxima interrupt the along-line flow by producing along-line decelerations as well as lateral pressure gradient accelerations toward either the line’s leading or trailing side (depending upon the location of the air parcel), in much the same way as upshear pressure maxima deflect environmental flow around supercells (Wilhelmson and Klemp 1978; Schlesinger 1980; Rotunno and Klemp 1982, etc.). As a result, the line’s interior has minimal along-line flow in time (Fig. 10a).

Statistical computations for large numbers of trajectories depict the following cycle: the typical updraft parcel undergoes minimal acceleration as it moves westward toward the convective line, experiences eastward and northward accelerations while ascending in an updraft, and then decelerates vertically while being displaced laterally away from the line’s axis. Therefore,

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Fig. 9. Projection of 3D trajectories onto Cartesian planes for the CS simulation. Trajectories begin at $t = 1$ h 30 min and extend through $t = 2$ h 30 min. The trajectories begin at the circles and are marked with a box at $t = 2$ h 5 min. The letters and line thicknesses are for reference and to assist in distinguishing among the trajectories (they have no other meaning).
the upper-tropospheric line-parallel flow field is weaker along the line’s axis than in the leading and trailing anvils. Most updraft air parcels in the simulated PS MCS acquire significant northward accelerations within the convective updrafts, but then lose their northward momentum and spread laterally as they encounter the pressure maximum that is upshear of the next updraft to the north. How then is the along-line flow maintained in the leading and trailing anvils? Statistics for large numbers of updraft trajectories reveal that as the air parcels diverge into the line-leading or line-trailing anvil, they acquire additional along-line accelerations that are associated with the system’s mesoscale buoyancy field.

There is system-scale differential advection of positively buoyant cloudy air northward in the upper troposphere, and advection of evaporatively chilled air southward in the lower troposphere. Additionally, due to the continual back-building there is a tendency for deep convective heating on the line’s southern side and for (stratiform) heating over chilling on the line’s northern side. These processes impart a tilted along-line structure to the buoyancy field (Fig. 11) that is accompanied by an along-line gradient in $\rho_p$ (contours in Fig. 10b). The presence of along-line shear within the convective region thus brings about a positive feedback because it produces a buoyant pressure field that reinforces the northward along-line flow aloft.

So, the integrated conceptual model is of updraft air
that receives large along-line (northward) accelerations during its ascent in convective updrafts (Fig. 12, location 1), then loses some of this along-line momentum as the $p'_B$ field associated with its (northern) along-line neighbor is felt (Fig. 12, location 2), followed by gradual reacquisition of along-line (northward) momentum owing to the weak but widespread gradient in the $p'_B$ field, which is associated with the system’s mesoscale structure (Fig. 12, location 3). Because, over time, the within-line $\nu$-wind speed and vertical shear are diminished (Part I), it must be the combination of the PS system’s back-building mechanism (providing for new convection on the line’s southern end) and the along-line northward mesoscale ACCB that maintain and reinforce the PS structure once it develops.

4. Sensitivities

The preceding picture of PS systems’ governing dynamics can be supported and extended by testing the simulation’s sensitivities to vertical wind shear and to along-line periodicity. As well, additional sensitivity tests serve to answer remaining questions about the possible impacts of the initial convective trigger and the environmental inertial stability.

a. Vertical wind shear

Bryan et al. (2004) found that a PS MCS from the Bow Echo and Mesoscale Convective Vortices (MCV) Experiment (BAMEX; Davis et al. 2004) had weak line-perpendicular shear in comparison to its cold pool strength (i.e., in the framework of Rotunno et al. 1988); they questioned how well the 2D interaction between a cold pool and shear would explain the 3D PS MCS structure. To assess the comparative roles of the line-perpendicular and line-parallel vertical wind shear, the CS simulation (which maintains its orientation with respect to the environmental wind profile) was rerun with both increased and decreased $u$ and $v$ wind shear (see section 2a and Fig. 1).
Increasing (decreasing) the line-parallel vertical wind shear in the CS runs increases (decreases) the along-line hydrometeor flux (Fig. 13), which in turn increases (decreases) the size of the line-parallel stratiform precipitation region (cf. Figs. 14a,d,e). In the first couple of hours this has a modest impact on the basic evolution of the CS run (cf. Fig. 14). As time goes on, the differences become more apparent (cf. Figs. 15a,d,e). Diagnostic calculations reveal that, in the very early going, differences among these $V_s$ sensitivity tests are related to the along-line ACCD, which is clearly linked to the line-parallel wind shear. As the mesoscale precipitation and buoyancy structures of the systems mature, the positive mesoscale feedback discussed in section 3 begins to occur, and there become notable differences in the along-line ACCB. Even as early as $t = 2$ h, the averaged along-line ACCB within the cloudy air for the CS-$1.5xVs$ simulation was roughly twice that of the CS run; ACCB for the CS-$0.5xVs$ was roughly half that for the CS run. In time these compounded differences in ACCD and ACCB lead to much larger and smaller line-parallel precipitation regions, respectively.

The CS-$1.5xVs$ simulation not only produces a larger PS region than do the CS and CS-$0.5xVs$ simulations, but it also better resists the seemingly inexorable march toward TS structure (Figs. 14 and 15a,d,e). These results are related: because the convective system experiences larger along-line accelerations, a greater amount of the system’s hydrometeor mass is advected away from the line into the PS region, and comparatively less falls in proximity to the preexisting cold pool. Therefore, even though the individual convective downdrafts are of comparable strength, the surface outflow is comparatively weaker in time for the CS-$1.5xVs$ simulation (at $t = 6$ h, for CS-$1.5xVs$: $\theta' = -5.9$ K, $p' = 1.19$ hPa; for CS: $\theta' = -7.4$ K, $p' = 1.62$ hPa). Together, these outcomes of stronger line-parallel shear can help an MCS retain PS structure for some time.

The impact of increasing or decreasing the low-level line-perpendicular shear is also unique. As suggested by Rotunno et al. (1988) and Weisman and Rotunno (2004), increasing the line-perpendicular shear results in convective cells that do not slope so severely rearward over the outflow. Therefore, even though the individual convective downdrafts are of comparable strength, the surface outflow is comparatively weaker in time for the CS-$1.5xVs$ simulation (at $t = 6$ h, for CS-$1.5xVs$: $\theta' = -5.9$ K, $p' = 1.19$ hPa; for CS: $\theta' = -7.4$ K, $p' = 1.62$ hPa). Together, these outcomes of stronger line-parallel shear can help an MCS retain PS structure for some time.

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As described in Part I, the PS structure can rapidly intensify the surface cold pool because most of the system’s precipitation falls out in close proximity to the surface gust front and because cells along the convective line tend to seed one another. The CS-$1.5xUs$ run exhibits this behavior even more so, because the convection is stronger and because the convective cores are

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6 In this article (as in Part I), cold pool strength is reported in terms of two values, each averaged over a $100 \times 100$ km$^2$ box that contains the coldest surface air. The first value is the surface temperature perturbation ($\theta'$). The second value is the increase in the pressure perturbation between 1100 m AGL and the surface; this surface pressure “excess” ($p'$) is an integrated measure of both the density perturbation of the outflow and its depth.
directly above the outflow boundary (Fig. 14c). Ironically, the low-level shear that initially provides for a strong, upright convective line in time brings about a large TS/PS hybrid (Fig. 15c), whose TS characteristics have come from the remarkable intensification of the outflow through this process. This simulation produced the strongest cold pool among all of the CS simulations (at $t = 5$ h, for CS-1.5xUs: $\theta' = -8.6$ K, $p' = 1.76$ hPa; for CS: $\theta' = -6.2$ K, $p' = 1.35$ hPa). Increasing both $U_s$ and $V_s$ leads to the greatest along-line hydrometeor transports (Fig. 13) and initially to the most prolific PS structure (Fig. 14f), but the CS-1.5xUs + 1.5xVs still succumbs to the rapid cold pool intensification and evolves toward TS structure (Fig. 15f). Overall, in the present experiment increasing the low-level line-perpendicular shear beyond what is necessary for regenerating convection is less beneficial for the PS mode than increasing the line-parallel shear.

Decreasing the low-level line-perpendicular shear, as predicted by Rotunno et al. (1988), yields a relatively small, weak convective system that can be considered a TS/PS hybrid, although at times its appearance is barely linelike (Figs. 14b and 15b). The line-parallel precipitation region is smaller because the along-line hydrometeor fluxes are weaker (Fig. 13), as a result of the diminished upward mass flux in the updrafts (19% less than the CS simulation at $t = 2$ h). Although not shown here, the CS and control simulations were also rerun without any line-perpendicular vertical wind shear (i.e., CS-0xUs); in these experiments, there was neither a PS MCS nor any long-lived convection after roughly two hours of simulation. Hence, as suggested earlier, some moderate amount of low-level line-perpendicular shear is required for PS MCSs, in addition to the need for line-parallel shear throughout the troposphere.

Fig. 14. Same as Fig. 2 but for all six CS simulations at $t = 3$ h. (a) CS run, (b) CS-0.5xUs run, (c) CS-1.5xUs run, (d) CS-0.5xVs run, (e) CS-1.5xVs run, (f) CS-1.5xUs + 1.5xVs run.
b. Three-dimensionality and line-end effects

In section 3, it was suggested that the along-line shape of the buoyancy field entails line-parallel ACCB in the near-line anvil regions. In this respect, line-end effects have a significant impact on the evolution of PS MCSs. This claim can be readily tested by rerunning the control and CS simulations with a Q2D, y-periodic model configuration (described in section 2a).

After 3 h of simulation, the fully 3D control run had already produced a PS/TS hybrid (Fig. 16a); in contrast, the Q2D control simulation produced no trailing precipitation by $t = 3$ h (Fig. 16b), which suggests an additional reason why the line-perpendicular shear is important. The generation of a trailing precipitation region is favored in the 3D control simulations because convection can occur where the outflow boundary-perpendicular component of the vertical wind shear is weaker (Fig. 17a). In these locales, air will experience comparatively small rear-to-fore line-perpendicular accelerations, and will tend to exit the convective region and move over the cold pool. In turn, parcels moving rearward over the cold pool will lead to the development of trailing precipitation behind the flanks of the original convective line. In contrast, development along these nonperpendicular flanks is impossible in the Q2D configuration (Fig. 17b). The above sensitivity

7 The fully 3D simulations with Coriolis accelerations (see Part I, section 5b and Part II, section 4d) also produce predominant cyclonic midlevel vortices, whose existence can be considered a line-end effect (e.g., Davis and Weisman 1994; Skamarock et al. 1994; Weisman and Davis 1998). Although they are not the focus of the present paper, such cyclonic vortices can lead to highly 3D MCS structures (e.g., Skamarock et al. 1994). However, as discussed in Part I, the cyclonic vortex is not a principal player in the PS–TS transition.
also occurs in the CS simulations (they are also more resistant to the PS–TS evolution in Q2D), although it appears to be less significant because the initial convective line is already perpendicular to the lower-tropospheric vertical wind shear in the 3D runs, and therefore produces a rather square (rather than circular) cold pool, with little or no development along the trailing shear-parallel flanks (e.g., Fig. 14a).

In addition, the surface cold pool is stronger in 3D than in the Q2D control simulations (at $t = 3\, h$, in 3D: $\theta' = -7.1\, K$, $p' = 1.46\, hPa$; in Q2D: $\theta' = -6.0\, K$, $p' = 1.15\, hPa$; the CS runs have similar sensitivity). Because the Q2D simulations are periodic, they are insulated from the dry environmental air that is present at the line ends in 3D. They therefore lack some of the evaporative chilling that is present in a finite-length line. Comparatively strengthening or weakening the surface cold pool also respectively tends to promote or dampen

![Conceptual model of accelerations associated with a surface cold pool and developing updrafts in the presence of lower-tropospheric vertical wind shear: (a) for the fully 3D model configuration; (b) for the Q2D model configuration.](image)

**Fig. 16.** Same as Fig. 2 but for (a) the fully 3D control run, and (b) the Q2D configuration of the control run at $t = 3\, h$. 
evolution toward the TS mode (Rotunno et al. 1988; Parker and Johnson 2004b; Part I, etc.).

Beyond the much-delayed evolution toward TS structure, when the along-line wind shear is varied in the Q2D CS runs, the line-parallel fluxes change in much the same way as in 3D (cf. Figs. 13 and 18), underscoring the importance of the ACCD associated with updrafts in line-parallel shear. However, it is even more important that the along-line fluxes are significantly diminished in going from 3D to the Q2D configuration (Fig. 18, for the CS simulations in which system reorientation is not at issue). Quite simply, air parcels in the anvil region aloft do not experience the along-line accelerations associated with the 3D $p/\theta$ field.

As discussed above and in Part I, air parcels are generally unable to flow along the line’s axis for significant distances because other cells farther down the line interrupt them. However, the along-line pressure gradient accelerations associated with the mesoscale buoyancy field provide persistent support for the along-line fluxes in the nearby anvil. As explained in section 3, this line-end effect relies upon the along-line variations in the vertical profile of buoyancy. When this effect is removed, the flow along the line’s axis continues to be interrupted, and the additional lack of line-parallel accelerations in the anvil regions cannot make up for it. So, it is the along-line fluxes that generate the characteristic 3D PS structure, and this three-dimensionality itself is important to the long-term sustenance of the along-line accelerations.

Because PS MCSs are fully 3D phenomena, the Q2D framework has limited practicality. However, the comparison between Q2D and 3D is valuable because it highlights 1) the relevance of finite line length to the evolution toward TS structure, and 2) the importance of line-end effects in reinforcing the line-parallel hydrometeor fluxes. In other words, there are both positive and negative feedbacks associated with the fully 3D PS structure.

c. Pattern and method of convective initiation

There is also some interest and concern over the degree to which the method of initiation controls the eventual organization of convection in idealized numerical simulations. The line thermal utilized in the present study may seem unreasonably restrictive. For example, Bluestein and Jain (1985) observed that severe squall lines are often initiated as broken lines. In addition, section 3 suggested that the strongly linear forcing of the surface outflow boundary can overwhelm or suppress the tendency for quasi-supercellular convection that might otherwise be expected in a high shear environment. To determine the degree of variability in convective storms that might occur in these environments, the simulations were rerun using lines of 1–5 axisymmetric warm bubbles as initial triggers [much as utilized by Skamarock et al. (1994), Weisman and Davis (1998), and Bluestein and Weisman (2000)]. These axisymmetric warm bubbles had the same temperature characteristics as the initial line thermal, but with a horizontal radius of 10 km, a vertical radius of 1.4 km, and a relative humidity set to 0.95.

The bubbles’ horizontal spacing varied between 50 and 100 km, which is somewhat greater than the spacings used by Skamarock et al. (1994), Weisman and Davis (1998), and Bluestein and Weisman (2000). The smaller spacings of the previous studies ensured more rapid cell interactions along the line, whereas for the present experiment the desire was to allow the initial convection to develop more independently for a while.

For one individual axisymmetric bubble in the control and CS environments, the convective behavior was distinct (e.g., Fig. 19). In both cases, quasi-supercellular behavior occurred initially, as updraft-flanking vortices

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8 This increase in relative humidity was necessary in order for the initially isolated storms to survive in the high-shear environment.
lead to storm splitting (much as in section 4). However, in neither case did convective storms remain after the first 2–3 h, and this result was insensitive to the strength and size of the initial warm bubble. In other words, the base-state environment was not particularly hospitable to isolated convective storms, likely due to the relative dryness of the sounding above the lower-tropospheric quasi-mixed layer. Parker and Johnson (2004c) noted that this sounding is characteristic of midlatitude MCS environments, but is considerably drier aloft than most commonly used model convection soundings (e.g., that of Weisman and Klemp 1982). Only strongly forced convection is able to survive in this environment. If the environment is moistened and CAPE is increased (i.e., using the MOIST profile of Parker and Johnson 2004c), the single-bubble control and CS simulations do indeed produce long-lived, more widespread convection (not shown); although such a thermodynamic sounding begins to strain the bounds of reasonable intercomparability with the original PS simulations.

With the inclusion of any number of additional, aligned bubbles in the control and CS simulations, the convection becomes long-lived and evolution to PS structure occurs along very similar pathways to the original simulations that used a long line thermal (e.g., Figs. 14, 15). However, with fewer bubbles the process of upscale organization occurs more slowly because it takes time to create a reasonably large and strong surface cold pool. When only two bubbles were included, they needed to be near one another in order to accomplish these effects. In an experiment in which the two axisymmetric bubbles were 100 km apart, short-lived, isolated storms developed because the initial storms were not close enough to interact and produce a combined cold pool. However, when the spacing of the two bubbles was reduced by one-third (to 66.7 km), a combined cold pool resulted, and a PS MCS developed slowly over time. When three or more axisymmetric bubbles were used, a PS MCS developed even for spacings as great as 100 km.

Bluestein and Weisman (2000) emphasized that the orientation of the deep-layer shear vector with respect to the convective line was a key discriminator between squall lines and isolated supercells. However, their simulations differed from the present ones in several important ways. Bluestein and Weisman (2000) added a cap to their environmental sounding in order to make it “more difficult to trigger secondary convection along outflow boundaries”. In addition to the cap, their simulations with significant along-line shear (especially with their choice of $\alpha = 0^\circ$) had only minimal line-perpendicular vertical wind shear on the inflow side of the convective line. According to the hypotheses of Weisman et al. (1988) and Weisman and Rotunno (2004), such weak line-normal shear would further inhibit redevelopment along the system’s gust front. For these reasons, as well as their exclusion of ice microphysics (see Part I), the simulations of Bluestein and Weisman (2000) did not produce PS MCs and were probably examining a different part of the moderate-high shear parameter space.

Even so, Bluestein and Weisman’s (2000) basic insight still applies: in high shear environments, a squall line develops after neighboring cells collide. In the present experiments, the deciding factor is the ability of an initial group of storms to produce a quasi-linear outflow boundary that is nearly perpendicular to the lower-tropospheric vertical wind shear vector (establishing a persistent region of intense lower-tropospheric lifting). As well, when more isolated storms are initiated in environments with along-line shear, the upshear/upline storms are able to seed the downshear/downline storms (much as in section 3), hence accelerating the rate at which they produce precipitation and outflow.

As a final test of sensitivity to the method of convective initiation, the control and CS simulations were started with an initial surface cold pool having a temperature perturbation of $-5$ K, a depth of 1.5 km, and a horizontal radius of 100 km. In this case, the results qualitatively differed very little from the line thermal simulations. Within the archetypal PS MCS wind profiles, when convective initiation is not completely isolated it is likely that the mesoscale organization of the convection will eventually resemble the PS structure. Once linear lifting is established in the control and CS environments, the PS structure naturally evolves.
d. Inertial stability

Inertial stability is the degree to which a fluid’s rotational constraint resists lateral parcel displacements (e.g., Schubert and Hack 1982). Blanchard et al. (1998) found that the strength of cloud-top divergence from mesoscale convective systems was strongly related to the inertial stability of the environment, as manifested through a significant sensitivity to the magnitude of the Coriolis parameter.

There is some suggestion (D. Schultz 2004, personal communication) that PS systems are often associated with middle- and upper-tropospheric cyclones. It makes sense that PS systems commonly occur under positive relative vorticity aloft since they commonly occur near the fronts of midlatitude surface cyclones (e.g., Parker and Johnson 2000; Part I). In such cases, the inertial stability would be quite high. Increased inertial stability would not preferentially enhance the along-line flow, but it would weaken the lateral (forward and rearward) cloud-top divergence that is superposed upon the main along-line current. In turn, this would lead to a narrower, archetypal PS structure. As in Blanchard et al. (1998), this possibility can be easily investigated by varying the base state’s Coriolis parameter, $f$. The control simulations used $f = 0$ s$^{-1}$, whereas the two sensitivity experiments incorporated $f = 1 \times 10^{-4}$ s$^{-1}$ and $f = 2 \times 10^{-4}$ s$^{-1}$, applied to the perturbation winds (only).

Increasing $f$ changed the organizational modes of the control and CS simulations very little through 6 h, even as some of the mesoscale details were a bit different (cf. Figs. 14a, 20a; Figs. 15a, 20b). The upper-tropospheric anvils were indeed slightly narrower, and by $t = 6$ h the size of regions with significant hydrometeor content (i.e., dBZ > 0) was also slightly smaller (cf. Figs. 15a, 20b). However, the simulated development of the PS mode is not impacted much by changes in $f$. In other words, even as inertial stability makes a detectable difference in the size of the cloud shield, it exhibits very weak or no control on the actual organizational mode (i.e., LS, PS, TS). Analysis shows that the pressure gradient accelerations in the convective region (e.g., section 3) far exceed the magnitude of the Coriolis accelerations. So, the suggested relationship to upper-tropospheric cyclones probably has more to do with where PS MCSs are triggered.

5. Synthesis

This paper and its companion (Parker 2007) have set forth a conceptual model for the development and evolution of linear convective systems with parallel stratiform precipitation (the PS mode presented by Parker and Johnson 2000). Such systems are a preferred mode for convective organization in environments with significant line-parallel vertical wind shear. The PS structure and more generally convective lines in environments with 3D wind profiles have heretofore received relatively little study. The present pair of articles have approached this problem through idealized numerical simulations, the basic details of which were compared to an analysis of a real-world PS MCS (from 2 May 1997; Part I) and found to be credible. Simulations using both an archetypal PS MCS wind profile and a pedagogical consolidated shear (CS) wind profile developed the characteristic PS structure and revealed...
many of its sensitivities. As a result, a consolidated view of PS MCSs, and more generally of convective evolution in environments with line-parallel vertical wind shear, has emerged.

There are two fundamental processes that can be isolated in the numerical model: one is an interaction between the cold pool and line-perpendicular wind shear that determines whether erect, forward-leaning, or rearward-leaning updrafts are preferentially produced. The role of line-perpendicular shear is much as Rotunno et al. (1988) originally envisioned, and leads to the development of either line-leading or line-trailing precipitation in time, as discussed by Parker and Johnson (2004a,b,c). The presence of significant vertical wind shear throughout the troposphere does indeed lead to storm splitting and quasi-supercellular elements due to tilting of environmental horizontal vorticity during the early stages of convective development. However, despite this three-dimensionality, the basic quasi-2D accelerations associated with lifting by the surface outflow boundary in line-perpendicular shear remain of first importance. Indeed, sensitivity tests reveal that without an appropriate amount of lower-tropospheric line-perpendicular wind shear, an archetypal PS structure is unlikely to emerge.

In addition to the long-established importance of the line-perpendicular wind shear, the simulations reveal that the presence of line-parallel wind shear is of prime importance in the development of the PS structure. Updraft air experiences along-line accelerations associated with a downshear-directed dynamic pressure gradient force. In time, these accelerations cause air parcels to acquire significant line-parallel velocities. These parcels then depart the convective region and carry their water content along the line, leading to a developing line-parallel precipitation zone.

Another salient impact of line-parallel vertical wind shear is that back-building occurs toward the convective line’s right (south in the simulations). In the present study, back-building is accomplished on the mesoscale via along-line expansion of the cold pool due to rightward (southward) hydrometeor advection. Equally importantly, back-building is also accomplished on the convective scale as downdrafts from individual convective cells bring forth rightward (southward) surges within the cold pool that favor the development of new cells to the right (south) of the previous cell. Just as along-line advection of hydrometeors favors development of the PS region to the line’s left (north in the simulations), back-building favors new convective development to the line’s right (south). These two processes in tandem promote the characteristic PS MCS structure in environments with line-parallel shear.

The preceding discussion emphasizes that both line-parallel and line-perpendicular vertical wind shear are necessary for the development of the PS structure. As a linear convective system in such an environment reaches maturity, however, both negative and positive feedbacks occur. In time, the along-line wind field within the axis of the convective line becomes weakened. This weakening occurs because air parcels are not able to flow immediately down the line’s axis; the pressure maxima associated with other convective cells farther down the line interfere with such air parcels and they are slowed and deflected laterally into either the line-leading or line-trailing anvils. A negative feedback linked to the PS structure is therefore that the presence of other cells along the line hinders the along-line hydrometeor fluxes. Instead, much of the along-line hydrometeor transport necessary for the development and sustenance of the line-parallel precipitation region occurs within these leading and trailing anvils, immediately adjacent to the axis of the convective line.

In this regard the buoyant pressure field is important and represents a positive feedback associated with the PS structure. Owing to differential advection and back-building, the mesoscale buoyancy field has an along-line slope. This slope in turn implies a horizontal buoyant pressure gradient acceleration. Although the acceleration is small in magnitude, it is widespread and air parcels within the leading and trailing anvils experience it for long periods of time. Over the course of an updraft parcel’s trajectory, the mesoscale buoyant pressure gradient accelerations associated with a mature PS MCS can therefore make up for the decelerations experienced due to interference from other updrafts farther down the line. The net result is reinforcement of the PS structure.

Yet another unique aspect brought about by the presence of line-parallel vertical wind shear is that the along-line motion of hydrometeors (mainly snow) in the upper troposphere can seed convective updrafts that are farther down the line. Such seeding can contribute to more rapid buoyancy reversal in updrafts and more rapid intensification of the surface cold pool. Also, many of the convective cells move along the line and therefore drop most of their precipitation very near the surface outflow boundary; this adds evaporative chilling preferentially along the cold pool’s leading edge, where it most directly impacts gust front lifting.

Because the above processes lead to rapid cold pool strengthening, convective lines in environments with line-parallel precipitation often evolve in short order from the characteristic PS structure toward the well-
known convective line with trailing stratiform (TS) precipitation structure. Following the above, many of the simulated sensitivities to the vertical wind profile hinged upon how rapidly this process of cold pool intensification and system evolution took place. The evolution toward TS structure was best resisted by simulated convective lines in environments with moderate lower-tropospheric line-perpendicular wind shear and large middle–upper-tropospheric line-parallel wind shear. Such systems were able to vent a great deal of their hydrometeors into the line-parallel precipitation region, implying less local evaporative chilling right at the main outflow boundary.

It is interesting in its own right that the resulting PS–TS hybrid structures are highly asymmetric, and that this asymmetry does not require Coriolis accelerations. The presence of line-parallel vertical wind shear is sufficient to bring about a highly asymmetric TS structure in time, much as discussed by Trier et al. (1997) and Hilgendorf and Johnson (1998). In addition to the steady evolution toward TS structure, the increasingly linear forcing associated with the outflow’s maturation also hinders the quasi-supercellular processes that were evident during the systems’ formative stages. The long-term viability of supercellular structures in the present experiment requires that the initial convection be fairly isolated, so that a combined mesoscale cold pool does not develop.

Because a great deal of convection research has focused on 2D and quasi-2D convective structures and simulations, it is also of interest that sensitivity tests reveal the importance of line-end effects in environments with line-parallel shear. First, three-dimensionality is important to the positive feedback associated with the along-line slope of the buoyancy field in PS MCSs, described above. However, three-dimensional systems also entrain more dry air and produce new storms along parts of their outflow boundaries where the line-perpendicular wind shear is sufficient for new convective development, and yet is overwhelmed by the outflow’s induced circulation. Hence, three-dimensionality ironically entails larger along-line hydrometeor fluxes, but also more rapid evolution toward TS structure.

The anecdotal suggestion that high inertial stability is important to the archetypal PS structure in the real world is not clearly supported. Strong inertial stability should limit the cross-stream extent of the anvil aloft, meaning that it would be comparatively narrow in across-line extent, perhaps making it look more like an archetypal PS system. However, the precipitation field itself is relatively insensitive to the value chosen for the model Coriolis parameter. In short, the presence of ad-equate line-perpendicular lower-tropospheric wind shear and deep line-parallel wind shear are the predominant factors that lead to the PS evolution outlined above. Such environments would seem to be common when convection is initiated along preexisting baroclinic zones, because thermal wind balance there implies a large degree of line-parallel wind shear.

6. Indicated future work

In the present work, an idealized homogeneous environment aided in interpretation of the basic processes that govern PS systems. In addition, a simplified consolidated shear environment served to help isolate the individual contributions of line-perpendicular and line-parallel wind shear to system dynamics. Simulations in more lifelike environments are a logical next step. In particular, it will be of interest to understand why convective systems with lower-tropospheric line-parallel shear in the real world retain their orientation with respect to the typically observed storm-relative wind profiles, without reorienting themselves. It may be that the inclusion of surface friction or more lifelike fronts can help to explain this apparent problem. Additional numerical studies with different microphysical schemes may also shed additional light on the importance of along-line hydrometeor transports and the impacts of convective cells that seed snow into their neighbors farther down the line. Finally, it will be important to generate observational case studies with sufficient resolution to address some of the hypotheses and conceptual models advanced in the present study. Toward this end, one such case study from BAMEX is currently ongoing (preliminarily reported by Halligan and Parker 2004).

7. Conclusions

The author utilized the Advanced Regional Prediction System (ARPS) to simulate linear convective systems with parallel stratiform (PS) precipitation, a favored mesoscale structure in environments with line-parallel vertical wind shear. This paper, along with Part I, constitutes perhaps the first thorough examination of PS systems. In addition, the study elaborates on other unique convective behaviors in environments with significant line-parallel shear. Section 5 of this article presents a consolidated depiction of the structures, governing dynamics, and mechanisms for maintenance and evolution of idealized, simulated PS systems, synthesizing and reviewing the results from both Parts I and II. This second paper specifically focused on the following chief results.
• Sensitivity tests reveal that both lower-tropospheric line-perpendicular wind shear and deep line-parallel wind shear are independently important to maintaining the PS structure. Systems with large line-parallel shear are able to retain PS structure the longest before evolving toward the production of trailing precipitation.
• The convective cells in PS systems are less independent from one another than in many other convective modes. The cells seed one another, and are also associated with dynamic pressure maxima that interfere with the along-line flow generated within updrafts farther up the line.
• Storm-relative along-line flow gives rise to a tilted mesoscale buoyancy field within the mature convective system, associated with which is an along-line pressure gradient acceleration. Therefore, the along-line velocity of convection-processed air in the line-leading and line-trailing anvils is slowly restored, re-inforcing the PS structure.
• Within the deep vertical wind shear of the simulated environments, splitting quasi-supercellular structures do initially develop. However, as their outflows merge and strengthen, the PS structure generally emerges and strongly linear cold pool forcing suppresses supercellular behavior.

The present study is a first step toward understanding the PS mode and convective systems in line-parallel wind shear. Because of their propensity for backbuilding and along-line cell movement, such MCSs are frequently implicated in flash flooding. Additional investigation of these little-studied systems therefore seems warranted.

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REFERENCES

