Simulated Convective Lines with Parallel Stratiform Precipitation.
Part I: An Archetype for Convection in Along-Line Shear

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ABSTRACT

This article, the first of two describing convective lines with parallel stratiform (PS) precipitation, addresses the basic kinematic and precipitation features of these systems. The PS mode appears to be the preferred organizational structure in environments with line-parallel vertical wind shear. This archetype for long-lived convective systems has received relatively little attention to date, and yet it is frequently implicated in flash flooding because it entails both the along-line movement of hydrometeors and back-building convective development. As a reality check, this paper presents conventional observations of the wind and reflectivity fields associated with an archetypal PS system from 2 May 1997. Thereafter, analyses of idealized numerical simulations serve as the basis for a more detailed investigation of PS systems’ internal structures and processes.

The observations and simulations suggest several unique aspects of the PS structure. The environment’s vertically sheared 3D wind profile helps to explain PS systems’ tendency to back-build, develop line-parallel precipitation, and evolve asymmetrically. Along-line flow within the system cold pool entails back-building on both the mesoscale and the convective scale. As well, along-line flow in the upper troposphere within the system entails along-line hydrometeor transports, especially in the leading and trailing anvils. These behaviors lead to the archetypal PS structure.

Along-line hydrometeor advection means that much of the system’s precipitation falls very near its outflow boundary, and that the convective cells can seed other updrafts farther down the line. As a result, PS systems in line-parallel shear can intensify their cold pools quite rapidly. As well, in time the PS structure is characterized by diminished upper-tropospheric along-line flow within its axis. These factors may hasten transition toward a predominantly rearward-sloped updraft and the production of trailing precipitation. Even in the absence of Coriolis accelerations, this evolutionary pathway leads to highly asymmetric structures, such as are commonly observed in midlatitudes.

The present introductory exposition of PS systems in deep tropospheric line-parallel wind shear sets the stage for a detailed investigation of their dynamics and sensitivities in a companion article.

1. Introduction

It has become increasingly clear in recent decades that mesoscale convective systems (MCSs) have great impact upon human society. Fritsch et al. (1986) showed that MCSs account for much of the growing season rainfall in the agriculturally vital Great Plains and, following the global study of Laing and Fritsch (1997), MCSs are now thought to be of similar importance to the water budgets of numerous other regions throughout the world. As reviewed by Fritsch and Forbes (2001), MCSs are also known to impact civilization by frequently producing severe weather (large hail, tornadoes and other damaging winds, and flash flooding). Indeed, Doswell et al. (1996) reported that a large fraction of flash floods are attributable to MCSs, and Schumacher and Johnson (2005) confirmed their importance in a study of extreme rain events.

In this regard, the organizational modes of convective systems are quite relevant. As explained by Doswell et al. (1996), the total point rainfall produced by a precipitation system is a function not only of the precipitation rate, but also of the system’s arrangement of convective and stratiform precipitation elements, and the system’s overall motion vector. Indeed, Fritsch and Carbone (2004) suggested that a key component in improving quantitative precipitation forecasts is the de-
termination of “critical environmental factors and variations thereof that affect the evolution, structure, and propagation of moist convection.” Furthermore, Snook and Gallus (2004) found that the type and frequency of severe weather reports varied noticeably among MCSs’ organizational modes. Toward such ends, Parker and Johnson (2000, hereafter PJ00) studied the organization of linear\(^1\) MCSs in the central United States, and found that there were three distinct horizontal reflectivity archetypes (Fig. 1), each of which had a unique arrangement of convective and stratiform precipitation and a unique motion speed.

The well-known convective line with trailing stratiform (TS) precipitation mode composed approximately 60% of the PJ00 study population, and has heretofore been widely studied (see, e.g., PJ00 for a partial list of references). However, a surprising result was that roughly 20% of the studied systems were best described by the convective line with leading stratiform (LS) precipitation archetype, and that roughly 20% were best described by the convective line with parallel stratiform (PS) precipitation archetype. These two less-traditional linear MCS archetypes are of particular interest to the flash flood problem: a large fraction of the extreme rain events documented by Schumacher and Johnson (2004) comprised nonclassical (i.e., not TS) MCSs.

Recent studies have addressed some elements of the dynamics, structures, and maintenance of LS MCSs, such as Pettet and Johnson (2003) and Parker and Johnson (2004a,b,c), in addition to earlier studies of quasi LS systems by Grady and Verlinde (1997) and Nachamkin et al. (2000). Along these lines, much of the discussion about evolutionary modes of linear convective systems has centered upon the relative strength of the line-perpendicular vertical wind shear (extending back through seminal papers by Thorpe et al. 1982; Rotunno et al. 1988). However, comparatively few studies have considered the possible impacts of along-line wind shear. It is perhaps for this reason that PS MCSs appear to have received little, if any, detailed attention as a kinematically and dynamically unique convective mode.

Even so, the paucity of studies on convective lines with parallel stratiform precipitation is somewhat surprising for several reasons. As discussed by PJ00 and Schumacher and Johnson (2005), other examples appear to include (based upon their published figures) those presented by Chappell (1986), Schwartz et al. (1990), Moore and Gagan (2000), Rogash and Smith (2000), and Roebber and Eise (2001). Snook and Gallus (2004) affirmed the frequency with which PS systems produce flooding and also noted that they were more frequently associated with very large hail (>5 cm diameter) than other MCS modes.

Parallel stratiform systems are of additional interest because they commonly arise in environments with significant deep-layer wind shear and clockwise-turning hodographs (e.g., PJ00; Parker et al. 2001), a situation that is also known to favor the development of supercell thunderstorms (e.g., Weisman and Klemp 1984; Moller et al. 1994). In this regard, an understanding of the unique character of PS MCSs seems to be highly relevant to the operational forecasting of convective evolution and severe weather. Indeed, Rogash and Racy (2002) found that significant tornadoes and flash floods can both occur within environments that are similar to those for PS MCSs documented by PJ00.

For the above reasons, a greater understanding of PS MCSs will likely contribute to improvements in the forecasting and warning of hazardous weather, and to deeper insight into the processes that govern all convective systems. As an initial step in that direction, the

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\(^1\) A linear MCS 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.

**Fig. 1.** Schematic reflectivity drawing of idealized life cycles for three linear MCS archetypes from Parker and Johnson (2000): (a) leading line with TS precipitation, (b) convective line with LS precipitation, (c) convective line with PS precipitation. Approximate time interval between phases: for TS 3–4 h; for LS 2–3 h; for PS 2–3 h. Levels of shading roughly correspond to 20, 40, and 50 dBZ.
present study comprised idealized simulations of convective lines with PS precipitation, using sensitivity tests and detailed analyses in order to probe their governing dynamics. The results are reported in this paper and its companion (Parker 2007, hereafter Part II).

a. Background

Byers and Braham (1949) noted that most storm elements within squall lines have some component of motion to the left of the system’s line-normal motion. In turn, Newton and Fankhauser (1964) were perhaps the first to point out that this might entail a significant along-line transport of hydrometeors, with the consequent development of a stratified line-parallel anvil cloud mass in which new storms were unlikely to develop. They also noted that, with respect to storm motion, the line’s right-hand side was the site of most rapid growth for new and young convective cells. This process, which is often referred to as back-building, was found to be frequent among severe squall lines by Bluestein and Jain (1985), and is not unique to quasi-PS systems. Nevertheless, rapid back-building to the right of a convective line’s motion can quickly lead to a characteristic PS structure, and was observed in many of the PS cases documented by PJ00.

It is of value to recall Bluestein and Jain (1985)’s observations that back-building squall lines tended to be initiated near a variety of surface boundaries, within environments that possessed strong vertical wind shear, significant helicity, and high CAPE. In other words, the Bluestein and Jain (1985) back-building squall lines occurred in environments that were similar to those for supercells. As mentioned earlier, the same properties are also shared by PS MCSs, and differentiating between the linear MCS and supercell environments is a salient research and forecasting problem. Bluestein and Weisman (2000) suggested that a key discriminator between the linear and supercellular modes is the orientation of the vertical wind shear vector with respect to any linear surface boundary that initiates convection. The present study compares and contrasts the internal processes and external factors governing PS MCSs to those for supercells (in Part II).

In addition to the above long-standing knowledge about back-building in squall lines, PS MCSs have sporadically made guest appearances in other papers about convective systems. For example, several of the weakly- to-moderately classifiable mesoscale precipitation systems depicted by Houze et al. (1990), their Figs. 13a,b, c have obvious PS MCS characteristics. Indeed, Houze et al. (1990) mention “convective lines with intense convection on their southern ends and weak convection and stratiform rain toward their northern ends” as a recognizable mode of organization within MCSs. It is of further interest to note that Schiesser et al. (1995) identified a recurring mode of organization in Swiss mesoscale precipitation systems in which a convective line was observed with little or no attendant stratiform precipitation. Parker (1999) speculated that such systems may indeed have had PS characteristics, except that their line-parallel precipitation was simply beyond the range of the radar coverage in the Schiesser et al. (1995) study. Finally, as has been mentioned, studies of large local precipitation episodes and flooding have also occasionally featured PS MCSs, although few such studies seem to have appeared in the refereed literature.

The wind profiles for Bluestein and Jain (1985)’s back-building cases and PJ00’s PS cases suggest that their environments typically possess lower-tropospheric line-perpendicular vertical wind shear (the importance of which is well known, e.g., Rotunno et al. 1988; Weisman and Rotunno 2004) in addition to deep tropospheric line-parallel shear. So, in some respects, PS systems can be thought of as a shear-parallel mode, as opposed to the TS and LS systems, which are shear-perpendicular modes (PJ00; Parker and Johnson 2004c). In addition to the preceding work, tropical and subtropical studies have revealed additional modes of shear-parallel precipitating convection, including cases in which the lower-tropospheric shear is minimal (LeMone et al. 1998), and cases in which the convection does not produce a strong surface cold pool and is parallel to the lower-tropospheric shear (Johnson et al. 2005). These examples are similar in appearance to midlatitude PS systems, but their organization is apparently linked to convective roll-like dynamics (Johnson et al. 2005), rather than to the interactions between surface cold pools and shear (e.g., Rotunno et al. 1988).

Along with such observational studies, many significant advances in our knowledge of convective systems and convective dynamics have arisen from idealized numerical modeling studies [see Wilhelmson and Wicker (2001), who recently reviewed many of them]. However, to this point, few if any of these studies have featured convective lines with PS precipitation. In part, this is no doubt attributable to the long-standing tradition of simulating linear convective systems in two-dimensional frameworks. Initially, this was necessitated

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2 Where left and right appear in this article, 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.
by limitations in computer memory and speed. And, even in the present day when large three-dimensional simulations of convection are both affordable and tractable, two-dimensional simulations of squall lines retain a great deal of pedagogical value.

Weisman et al. (1988) performed several quasi-2D simulations in which the linear vertical wind shear had an along-line component. Unfortunately, quasi-2D theories or simulations exclude the possibility of the PS mode. Even as fully 3D grids have increasingly become the norm for MCS simulations, many idealized modeling studies continue to utilize 2D wind profiles in order to understand the basic sensitivities and building blocks of organized convection. The simulations presented by UCAR (1999) and Bluestein and Weisman (2000) are salient exceptions, because they used a finite-length linear trigger for convection and included several environments with along-line shear. However, even these simulations did not produce PS MCSs. Much as Parker and Johnson (2004a) noted the need for ice microphysics in order to replicate the LS mode, the lack of ice microphysics used in the UCAR (1999) and Bluestein and Weisman (2000) simulations at least partly accounts for their inability to replicate the PS mode. With only Kessler (1969) microphysics, models produce hydrometeors that fall out too rapidly, limiting the size of stratiform regions (Fovell and Ogura 1988, etc.) and overstrengthening surface outflows because of too much evaporative chilling in the convective region. Beyond the above, when fully 3D simulations have been performed with 3D wind profiles, these simulations have often been intended to study supercells, and hence have featured convection that was initiated by a single warm bubble (e.g., Weisman and Klemp 1984). In such cases, it seems likely that isolated convection will be favored over linear modes (this is addressed in Part II).

The present study aims to eliminate a gap in the knowledge base by describing the governing dynamics of convective lines with PS precipitation. Owing to the lack of high-resolution research datasets at the present time, we analyze results from fully three-dimensional, convection-resolving simulations of PS MCSs. Therefore, as detailed above, the present effort also stands to fill a gap in the lineage of linear MCS modeling research. As a reality check, the model results are also briefly compared to some coarse, conventional observations of PS MCSs. Together with the observations, the simulations provide perhaps the first Consolidated physical view of convective lines with PS precipitation.

b. Structure of this paper

Section 2 of this paper presents observations from an archetypal PS MCS, which are meant to serve as both motivation and verification for the idealized simulations that follow. Section 3 then presents the methods used for the numerical simulations in this study. Thereafter, the paper discusses the basic structures of the simulated PS systems. The paper then concludes with a brief summary, setting the stage for Part II, which addresses the dynamics governing the development of simulated PS systems and their associated sensitivities.

2. Preliminary observations

Prior to undertaking idealized numerical simulations, it would be useful to consider what convective lines with PS precipitation are like in the real world. As mentioned in section 1, there has been no concerted prior effort to detail the interior structures and flow fields of PS MCSs. Among the linear MCSs documented by PJ00 was an archetypal PS system that occurred on 2 May 1997 (Figs. 2–3; PJ00’s Fig. 7c). The 2 May MCS formed in far southwestern Kansas around 2200 UTC 1 May 1997, and displayed characteristic PS structure from roughly 2300–0430 UTC as it moved southeastward into Texas and Oklahoma. Thereafter, the MCS evolved from PS toward TS structure, and eventually decayed. An analysis of this case during its PS phase serves as a reality check for the present study.3

a. Data utilized

During its early PS phase, the 2 May MCS was comparatively well-sampled considering the general sparseness of conventional operational observations. The 2 May PS MCS passed directly over the Vici, Oklahoma, National Oceanic and Atmospheric Administration (NOAA) Profiler Network site at roughly 0200 UTC, which provided a representative view of the presystem environmental wind profile (Fig. 4). In addition, at roughly 0100 UTC the convective line was within 70 km of the Dodge City, Kansas (KDDC), Weather Surveillance Radar-1988 Doppler (WSR-88D), and its closest segment was nearly perpendicular to the radar beam that sampled it (Fig. 2). The KDDC data provided for a reasonably finescale view of the PS system’s structure and line-perpendicular flow field. Then, approximately 80 min later (around 0220 UTC), the convective line was within 70 km of the Amarillo, Texas (KAMA), WSR-88D, and its closest segment was nearly parallel

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3 The environment for the 2 May system was not identical to the mean profiles used in the simulations that follow. The case was selected for presentation because its interior flow fields were much better depicted by the available radar observations than are most PS systems'.
to the radar beam that sampled it (Fig. 3). The KAMA data provided for a second look at the system’s structure, as well as a reasonably finescale view of its line-parallel flow field. Although the two radars sampled different parts of the convective line, and the line may have evolved somewhat in the intervening 80–90 min, these snapshots can be assembled into what is perhaps the first consolidated structural model of a convective line with PS precipitation.

b. Observed structures

The 2 May 1997 convective system occurred within a vertical wind profile that had two of the predominant features that PJ00 found to be common to PS MCSs (Fig. 4): lower-tropospheric line-perpendicular wind shear, and line-parallel vertical shear with along-line flow in the upper troposphere directed to the left of the system’s motion (cf. PJ00’s Fig. 12).

Early in the MCS’s archetypal PS phase, the KDDC radar sampled the convection near the line’s center (Fig. 2). The along-line cross section reveals three reflectivity cells of moderate depth and intensity (exceeding 40 dBZ; Fig. 2c). There is some suggestion that the cells leaned toward the northeast (i.e., the line’s “left,” particularly near y = 0 km in Fig. 2c), which is consistent with the direction of both the line-parallel vertical wind shear and the upper-tropospheric line-parallel storm-relative flow (Fig. 4). In association with the observed along-line flow, the cells also traveled along the line in a system-relative sense (Fig. 4). A line-normal cross section reveals that the strongest of the precipitation cores also leaned forward slightly, with a small
line-leading region of overhanging precipitation (Fig. 2b); these symptoms are quite consistent with the environment’s (Fig. 4) significant rear-to-fore component of the line-perpendicular shear (e.g., Rotunno et al. 1988; Parker and Johnson 2004b,c; Weisman and Rotunno 2004). A combined analysis implies low-level flow that was predominantly easterly and upper-level flow that was predominantly westerly within the convective line, which nicely explains the general eastward tilt of the reflectivity cores with height.

Later, during the PS MCS’s mature stage, the KAMA radar sampled the intense convection near the line’s southwestern (“right”) end (Fig. 3). The general values of reflectivity were higher for this segment of the line than what was measured earlier by the KDDC radar. Much of the line’s interior region exceeded 40 dBZ, with two cells exceeding 50 dBZ (Fig. 3c). Additionally, all of the line-parallel flow throughout the line’s depth was northeastward (toward the line’s left; Figs. 3b,c). Although the earlier KDDC observation suggested some along-line tilt to the convective cells, it is not plainly evident in Fig. 3c. This change may be related to the greater age of the convective system, as previous authors have suggested that line convection mixes line-parallel momentum downgradient, which would remove the along-line shear within the convective region (e.g., LeMone 1983). Indeed, the along-line flow field had minimal vertical shear along the line’s

**Fig. 3.** Data from the KAMA WSR-88D for the volume scan beginning 0222:59 UTC 2 May 1997. (a) Base scan (0.5° elevation angle) reflectivity (dBZ, shaded as shown); (b) line-perpendicular vertical cross section of reflectivity [dBZ, shaded as in (a)] and radial velocity (contoured every 5 m s⁻¹); (c) line-parallel vertical cross section of reflectivity [dBZ, shaded as in (a)] and radial velocity (contoured every 5 m s⁻¹). The locations of the KAMA radar and of vertical cross sections b–B and c–C are shown in (a). The point of intersection of the vertical cross sections is shown in (b), (c) as a white dashed line. The radar beam is perpendicular to cross section b–B at the black dashed line. The general direction of the flow field is shown by vector symbols at the maxima in (b), (c). Because it is not well resolved by the shading scale, the position of a radar fineline is also indicated.
axis (Figs. 3b,c). The lack of along-line tilt could also be a consequence of the convective updrafts being stronger: this would be consistent with the comparatively higher reflectivities and also with more upright updrafts.

The later line-perpendicular cross section from KAMA also reveals more preline than postline hydrometeors aloft (Fig. 3b), suggesting that the fundamental overturning nature of the updraft circulation persisted from the time of the earlier KDDC measurement. Notably, along the line’s axis the line-parallel flow had minimal vertical shear, whereas toward the line’s flanks it increased more dramatically with height through the lower and middle troposphere (Fig. 3b). The deep, nearly vertical core of 15–20 m s$^{-1}$ along-line flow near $x = 0$ km would be consistent with the vertical transport of line-parallel momentum with minimal acceleration, as mentioned above. Alternatively, the presence of the convective updrafts themselves could interrupt the along-line flow; this hypothesis is addressed in Part II using simulations. In either case, such behavior would be unique to the line’s axis, and would account for the relative minimum there in both the along-line flow and the along-line vertical shear. Although not presented here, this within-line minimum in radial velocity was also evident in many other line-perpendicular cross sections and also in parts of the line that were farther away than what is depicted in Fig. 3c.

c. Conceptual model of a convective line with PS precipitation

Based upon the 2 May 1997 PS MCS summarized above, as well as characteristics inferred from the relevant literature (e.g., Bluestein and Jain 1985; PJ00; Parker et al. 2001, as summarized in section 1), a conceptual model of convective lines with PS precipitation is presented in Fig. 5. The lower-tropospheric inflow is mainly directed from front-to-rear, although it may also have a weak along-line system-relative component. The environment’s deep layer shear vector has both a line-normal (rear-to-front oriented) component and a line-parallel component. The environmental flow aloft is therefore largely parallel to the convective line.

A region of intense convection is located above a surface outflow boundary/gust front, which may be the leading edge of a cold pool. This property is inferred from a fine line sampled by the KAMA radar, weakly evinced in Fig. 3 by 10 dBZ echoes to the east and south of KAMA; from observations at Gage, Oklahoma, where upon the line’s passage the temperature fell 5 K, the pressure rose 3 hPa, and the wind shifted 150$^\circ$; and from the near ubiquity of surface cold pools in other observational and numerical studies of convective lines.

Convective updrafts result from lifting at the edge of the cold pool. Accelerations within these updrafts have a rear-to-fore component that removes the front-to-rear storm-relative momentum of the inflow, sometimes causing the updrafts to overturn. Along-line accelerations result in significant along-line flow in the middle and upper troposphere of the convective line, directed to the left of the system motion vector. The along-line flow may be weaker within the axis of the convective line, however. The predominantly along-line flow in the anvil leads to the generation of the line-parallel region of precipitation, and engenders minimal line-perpendicular transport of hydrometeors, such that the footprint of the PS MCS is a relatively narrow swath of precipitation with large gradients on either side.

This conceptual model is of necessity somewhat coarse, owing to the lack of detailed case studies in the extant literature; however, it is representative of the characteristics of the 2 May 1997 PS MCS, as well as numerous others studied by the author, both formally and informally. And, even though it was originally developed independently from the simulations that follow, this conceptual model is also consistent with the structures and flow trajectories produced by the simulations. This point is worth noting because, for example,
the split flow aloft cannot be unambiguously derived from the available observations. Given the limitations of such conventional operational observations, it is encouraging that data from the recent Bow Echo and Mesoscale Convective Vortex Experiment (BAMEX; Davis et al. 2004) may offer the possibility of refining this model with finer scale investigations of PS systems in the future (e.g., the preliminary work of Halligan and Parker 2004).

3. Methods for the numerical experiments

This study made use of idealized numerical simulations to describe the basic evolutions and dynamics of PS MCSs. Numerical modeling techniques are desirable for attacking this problem because of their suitability for sensitivity tests as well as the paucity of high-resolution observations available for large sets of in-depth case studies. The study incorporated 3D simulations using version 5.1.0 of the Advanced Regional Prediction System (ARPS), a fully compressible non-hydrostatic model (Xue et al. 2000, 2001).

The basic model configuration was generally that used by Parker and Johnson (2004c). To explicitly simulate convective clouds on the \(600 \times 600 \times 20\) km\(^3\) domain, the simulations had horizontal grid spacings of 1 km, with an averaged vertical grid spacing of 400 m, ranging from 200 m in the lowest 2 km of the domain to 625 m in the model stratosphere. Trial and error revealed that a domain size of 600 km in the across- and along-line dimensions was large enough to simulate PS MCSs without having the lateral boundary conditions add appreciable error. The domain had rigid, free-slip conditions on both the upper and lower boundaries, and a Rayleigh damping layer in the stratosphere (the uppermost 7 km of the domain). The simulations had a large time step of 2.5 s and a small (acoustic) time step of 1.25 s (with implicit differencing in the vertical). The model used a 1.5-order turbulence kinetic energy (TKE) based closure. To damp very short waves and prevent instabilities on the domain, the model also included fourth order computational mixing, an Asselin time filter, and divergence damping. The model’s lateral boundaries had a wave radiating (open) boundary

![Fig. 5. Conceptual model, based on compiled radar observations, of a convective line with PS precipitation, viewed in a schematic three-dimensional rendering in which the orientation of the vertical planes is perpendicular to the convective line and parallel to its motion. The basic streamlines are indicated by the black arrows. The system’s cold pool is depicted by the dashed outlines and outflow boundary symbol. The radar reflectivity is shown in cross section and at the surface by shading, with contour levels corresponding to roughly 20, 40, and 50 dBZ. The typical orientation of the deep-layer shear vector is shown by the white arrow. Approximate horizontal and vertical scales are indicated, as are the orientations of the line-relative directions discussed in the text.](image-url)
condition. The control simulations did not include Coriolis accelerations, radiative effects, or surface fluxes. The simulations used an ice microphysics scheme based on those from Lin et al. (1983) and Tao and Simpson (1993).

The initial sounding was the idealized Parker and Johnson (2004c) midlatitude MCS sounding, using a smoothed storm-relative wind profile derived from an average of four archetypal PS MCS cases from the original PJ00 dataset (“control” in Fig. 6). This control wind profile is somewhat different from the overall PS mean from PJ00 (i.e., their Fig. 12), which was an average for 15 cases; the archetypal/control profile has a good deal more line-parallel shear. The control profile is also different from that of the 2 May 1997 PS MCS (Fig. 4): the 2 May case was attractive because it was very well-observed, but its environment had more line-perpendicular vertical wind shear than the control profile (e.g., Fig. 6). Because the control simulations that follow possess many of the same features as the observed 2 May 1997 MCS, one might therefore infer that the line-perpendicular shear is less relevant to PS MCSs than the line-parallel shear; this hypothesis is specifically addressed with sensitivity tests in Part II.

Ultimately, the control profile is a compromise between the desire for generality and the need to avoid the excessive smoothing that comes from averaging a large number of unique (and often nonarchetypal) cases; based upon the author’s experience, the profile is credible. In addition to the control wind profile, for reasons that will be discussed in section 4 and in Part II, it was also useful to isolate all of the control sounding’s line-perpendicular (i.e., u wind) shear to the 0–3 km layer, and all of the line-parallel (i.e., v wind) shear to the 3–10 km layer (the compartmentalized shear, or CS, profile; Fig. 6). For all of these wind profiles, the model was configured such that y was the along-line coordinate,4 and x was the across-line coordinate.

To initiate convection the model included a 200 km long, north–south linear warm bubble (+3 K) with random temperature perturbations (±0.3 K); this was a simple way to ensure that the initial convection in the model was linear, and was properly oriented with respect to the base-state wind profile. This line thermal had an east–west radius of 10 km and a vertical radius of 1.4 km. Parker and Johnson (2004a,b,c) utilized an initial cold box in order to initiate convection in their simulations of LS and TS MCSs. Their motivation included PJ00’s observation that almost all linear MCSs are initiated near linear surface boundaries in nature. In Part II of the present study, a cold box is indeed used for comparison (as well as other warm bubble configurations). However, because the wind profile in the PS cases is no longer 2D (as it was for the LS and TS simulations), it became instructive to allow the convective system to develop a cold pool on its own that was

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4 The Cartesian directions are used interchangeably with line-parallel and line-perpendicular throughout. Because the Coriolis parameter is constant in these simulations, there is no particular significance to the orientation of north, south, east, and west. However, many previous readers found these cardinal directions to be more intuitive than their complements, respectively: leftward, rightward, forward, and rearward.
physically consistent with the environmental flow direction and shear.

4. Basic structures in the control simulation

a. Organizing phase

The initial line thermal extended from \( y = 200 – 400 \) km and, after 1 h, the convective cells extend roughly from \( y = 230 – 370 \) km (Fig. 7a). The line ends are not sites for continuing convective redevelopment during the early part of the simulation because the pool of cold outflow is weaker and shallower there (not shown). The basic features of the system’s early evolution are that the cold pool expands southward and westward\(^5\) (Fig. 7a), consistent with its low-level storm-relative north-easterlies (Fig. 7b), and that line-parallel stratiform precipitation extends roughly 70 km northward from the northernmost convective core (at \( y = 360 \) km in Fig. 7a), consistent with upper-level storm-relative southerlies within the convective region (Fig. 7b). New development occurs on the line’s southern flank along the outflow boundary, whereas the evaporative chilling to the line’s north in the PS region is not sufficient to produce a significant cold pool and initiate new storms there.

These general behaviors of the simulated PS system mirror two of the primary features noted in real-world PS systems by PJ00. The first realistic feature is that convection-processed air acquires along-line momentum such that hydrometeors aloft are observed to move along the line in a system-relative sense (toward the north in Fig. 7a). The second realistic feature is that the convective line back-builds, with new cells developing on the system’s southern end as the cold pool expands southward; this phenomenon is explored in more detail in section 5. In an environment with significant line-parallel shear, the two behaviors go hand-in-hand, and they continue throughout the simulated PS organizational phase.

In order for a convective system to create a line-parallel precipitation region, there must be along-line flow in the zone of enhanced total water content. In other words, the flow field within the convective region of a PS MCS must be line-parallel (e.g., Fig. 7b). Animations of the control run are consistent with Fig. 7b, revealing that upper-tropospheric hydrometeors move largely northward, whereas lower-tropospheric hydrometeors have a southward component of motion. Notably, the most intense hydrometeor cores themselves do not move along the line very much because the heaviest precipitation falls out very near where it is produced. However, once convection-processed air has diverged from the cells aloft into the narrow along-line anvils, the line-parallel flow is much larger (Fig. 7b), much as was observed in the 2 May 1997 case (Fig. 3). To some extent, this is consistent with the conservation and downgradient transport of line-parallel momentum by the convective updrafts (as suggested, e.g., by LeMone 1983). However, because the low-level storm-relative flow is northerly (Fig. 6), it is evident that sig-

\(^{5}\) As a reminder, in a storm-relative sense the cold pool expands rearward and toward the right of the line’s inflow side. Such generality applies to all of the simulations whenever cardinal directions are used to describe them.
A 3D view of the control simulation during the early going reveals several additional similarities to the 2 May 1997 PS MCS, supporting the credibility of the idealized simulation. Both the real and simulated MCSs contain convective cells that lean downshear; that is, both eastward (Figs. 2b, 3b, and the $z$ versus $x$ panel of Fig. 8) and northward (Fig. 2b and the $z$ versus $y$ panel of Fig. 8). As well, in both MCSs the along-line wind component has cellular structure, with updrafts possessing a greater component of front-to-rear flow than their surroundings.

For the young updraft in Fig. 8, the strong westward lower-tropospheric inflow has been slowed such that the line-perpendicular velocity near the updraft’s top (around 8 km AGL) is near zero, although it has not yet overturned. A weak mean overturning updraft is evident in the along-line averaged fields (Fig. 7b), but it is less pronounced in the control simulation than in the 2 May 1997 PS MCS, likely because the idealized control wind profile has less line-perpendicular vertical wind shear (Fig. 6), whose importance to overturning updrafts is well documented (e.g., Rotunno et al. 1988; Parker and Johnson 2004a).

However, the along-line flow near the updraft’s top has a distinctly overturning flavor, with pronounced northward flow above 5 km AGL. The along-line accelerations must be significant to accomplish this, but the $y$ versus $x$ depiction nevertheless reveals that this

$\text{Fig. 8. Cartesian planes passing through } x = 274 \text{ km, } y = 297 \text{ km, } z = 8 \text{ km (near the top of a young updraft), for the control PS MCS simulation at } t = 1 \text{ h. Simulated radar reflectivity is shaded (dBZ), with wind vectors (m s}^{-1}\text{) scaled as shown; (lower left) } y \text{ vs } x \text{ plot at } z = 8 \text{ km; (upper left) } z \text{ vs } x \text{ plot at } y = 297 \text{ km; (lower right) } z \text{ vs } y \text{ plot at } x = 274 \text{ km. The location of each plot is shown in the other panels with a thin line.}$

\[\text{Although this term is often reserved for the line-perpendicular draft circulation, it is evident that air that originally possessed southward momentum has acquired northward momentum, and hence has overturned in the along-line direction.}\]
along-line flow in the upper part of the updraft is still weaker than that in its surroundings. As well, it is evident that the along-line flow is partly stagnated on the southern side of the updraft (the $z$ versus $y$ panel of Fig. 8). Because of these effects, the averaged $v$-wind values in the upper troposphere within the convective line are nearly constant from 4 to 11 km AGL (Fig. 7b). Therefore, in a mean sense the PS system diminishes the line-parallel shear in its immediate vicinity, although this is somewhat more complicated than a simple down-gradient mixing process.

By $t = 2$ h, it is clear that a line-parallel region of precipitation is developing toward the north (Fig. 9a) as a result of the northward accelerations imposed on air processed by the convection. The convective line also has slightly favored the production of leading precipitation over trailing precipitation prior to this time (Figs. 7b and 9a), much as did the 2 May 1997 case (Figs. 2b and 3b). The preference for leading precipitation results from two primary facts. First, the lower-tropospheric shear vector has a significant eastward component (Fig. 6a), which is important to the development of line-leading precipitation as discussed by Parker and Johnson (2004a,b,c). And second, the lower-tropospheric cold pool has not yet increased to its mature strength. The cold pool at $t = 2$ h has a surface temperature deficit of $-5.8$ K, and a surface pressure excess of 1.06 hPa. Nevertheless, by this time the early stages of a mean, westward-sloping updraft have started to become apparent (Fig. 9b), even as air also continues to flow eastward in the overturning updraft (east of $x = 270$ km in Fig. 9b). Much like the front-fed LS systems simulated by Parker and Johnson (2004a), the heaviest precipitation is aft of the surface outflow boundary. Updraft air drops much of its heavy precipitation during the westward portion of its ascent, before feeding hydrometeors to the parallel, leading, and trailing anvils.

### b. Mature phase

Because of along-line cell motions and line-parallel hydrometeor advection, much of a PS system’s precipitation falls out very near its outflow boundary, which in turn helps to rapidly intensify the outflow’s leading edge. As the simulated system begins to mature by $t = \ldots$ 3 h, the cold pool strength has increased, with an along-line averaged temperature deficit of $-7.1$ K, and increasing depth as evidenced by its surface pressure excess of 1.46 hPa. By this time, the system has the look of a mature PS MCS, with a long line and a region of line-parallel precipitation extending more than 100 km past the end of the convective line (Fig. 10a). The convective line has also begun to exhibit trailing precipitation in addition to the small leading precipitation region that it developed previously. In part this is attributable to the onset of weak forward motion of the convective line, which has progressed roughly 10 km eastward over the past hour owing to the strengthened cold pool. However, the intensification of the cold pool is also a significant factor in terms of the strongly rearward accelerations that it produces upon air parcels that it lifts (Rotunno et al. 1988; Parker and Johnson 2004c; Weisman and Rotunno 2004, among many others). At this time, most of...
Both the $u$ and $v$ components (Fig. 6), the control PS system in time tends to reorient itself toward a northwest–southeast line (Fig. 11). The simulations with along-line shear from UCAR (1999) undergo a similar evolution. Such reorientation is undesirable for an exploration of the dynamics of PS MCSs, because the upper-level environmental flow is no longer line-parallel. Parallel stratiform MCSs in the real world do not commonly evolve in this way, probably because they tend to be triggered along preexisting linear boundaries such as cold fronts (PJ00), which serve to maintain their orientation. However, initiating the convection with an infinitely long cold pool would remove the PS system’s distinctly 3D character. More complicated synoptic features are beyond the scope of the present, idealized study: this is a first attempt. Instead, by compartmentalizing the line-parallel shear to the layer above 3 km AGL (the CS profile; Fig. 6), it was possible to simulate convective lines that preserved their orientation with respect to the base-state wind profile, and then later to test their sensitivity to the strength of the line-parallel and line-perpendicular shear (discussed in Part II).

### a. Unique aspects of CS evolution

With compartmentalized shear, the simulated convective system maintains its north–south orientation through the 6-h simulation (Fig. 12) and, although it evolves toward a TS/PS hybrid in time, it maintains a fairly archetypal PS structure through roughly $t = 4$ h (e.g., Fig. 12b). These features make the CS simulation more amenable to the analyses in the later parts of section 5, while still sharing the principal elements of the control simulation. As in the control run, the CS run
exhibits both northward along-line advection of hydrometeors in the anvil and southward back-building (Figs. 12b and 12c; the original convection was initiated between \( y = 200 \) and 400 km). As well, much as in the 2 May 1997 case and the control simulation, the CS experiment exhibits along-line flow that is significant within its anvil precipitation region and is minimized within the axis of the convective line (Fig. 13).

The CS convective line does not intensify its surface cold pool as rapidly as in the control simulation. In part this is attributable to the smaller total condensate produced in the simulation (cf. Figs. 10a and 12b). Whereas updraft strengths are similar in the two simulations, the control simulation produces convection along a larger segment of its outflow boundary (cf. Figs. 10a and 12b) owing to the presence of adequate lower-tropospheric vertical wind shear along both its eastern and northern flanks (i.e., westerly and southerly wind shear components; Fig. 6). Because of its weaker cold pool, in addition to the slightly enhanced environmental line-perpendicular low-level wind shear (Fig. 6a), the updrafts after 3 h of the CS simulation are still fairly upright and continue to have a significant overturning component (Fig. 13). The CS run resists the evolution toward TS structure longer than the control run for these reasons. Notably, the real world MCS of 2 May 1997 preserved its mature PS characteristics for in excess of 5 h within an environment that had even more line-perpendicular shear (Fig. 6).

### b. Along-line hydrometeor transports

The simulated PS systems and the observed 2 May 1997 case study all exhibit maximized along-line flow within the line-leading and trailing anvil regions (Fig. 13; cf. Fig. 7b, etc.), rather than within the core of peak hydrometeor content. An interesting question is whether the along-line water fluxes that lead to the developing line-parallel precipitation are most dependent upon the high water content of the heavy convective cores or upon the strong along-line flow nearby, within the region of lower water content. The following discussion focuses on the along-line hydrometeor fluxes at \( t = 2 \) h when the CS system’s evolution toward TS structure is not yet evident in either the reflectivity (Fig. 12a) or transport fields (discussed below).

Below 5 km AGL in the CS simulation at \( t = 2 \) h, the along-line fluxes are almost entirely southward (Fig. 14), meaning that water transports in the lower-to-middle troposphere do not account for any along-line advection into the PS region. However, these southward transports do help to account for the southward...
expansion of the convective system in a storm-relative sense. As lower-tropospheric hydrometeors are ad
tected southward along the line in the simulations, they contribute to evaporative chilling that develops and re
inforces the cold pool on the line’s southern side. Preferential chilling on the line’s southern side can there
fore play a role in the PS back-building process.

In the middle and upper troposphere, during the de
velopmental stages of the simulated PS system, the along-line water fluxes are nearly zero within the axis of maximum hydrometeor content, and are significantly northward only in the leading and trailing anvils be
 tween roughly 5 and 12 km AGL (Fig. 14, Fig. 15 from
$\Delta t = 1$–3 h). The input of hydrometeors into the leading and trailing anvils occurs primarily between 8 and 11 km AGL as a result of forward and rearward flows that exit the convective region (e.g., Fig. 13). Beneath 8 km AGL and within 5 km on either side of the convective line, there is a narrow zone in which these hydrometeors fall into the relatively undisturbed along-line environmental flow that exists beneath the main anvils be
 tween roughly 6 and 7 km AGL (e.g., Fig. 13). The small-scale maxima in the along-line fluxes (Fig. 14), which fall between 6 and 8 km AGL, are attributable to the northward transport of this falling precipitation by the environmental flow. However, most of the along-
line fluxes that lead to the PS region occur within the convection-processed air throughout the remainder of the leading and trailing anvils, rather than in the shallow belt of environmental along-line flow.

As previously mentioned, the simulated systems evolve from PS toward TS structure. It is worth noting,
however, that even as this evolution occurs, the along-
line hydrometeor fluxes remain significant (Fig. 15). As its cold pool intensifies around $\Delta t = 2$ h, the CS system begins to move eastward with increasing speed (as is evident in Fig. 15). While this occurs, the along-line fluxes on the line’s trailing side (to the west in Fig. 15) become more diffuse, and the minimum within the con
vective region becomes correspondingly less distinct. As the system evolves toward TS structure, the north
ward along-line fluxes are distributed throughout the entirety of the broad, line-trailing, westward flow
stream. Therefore, even though mass is being fluxed largely rearward as a part of the PS–TS evolution, the mechanism responsible for along-line accelerations during the early going must still be present in some form during the later TS stages; this is addressed further in Part II. Clearly, such a combination of northward and westward hydrometeor transports would promote the kinds of asymmetric PS/TS hybrids that are often observed both in nature (Houze et al. 1990; Loehrer

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**Fig. 14.** Output for CS simulation at $\Delta t = 2$ h. Vertical cross section of along-line averaged (from $y = 220$–320 km; cf. Fig. 12a) radar reflectivity (simulated), shaded, with the along-line hydrometeor flux contoured ($3 \times 10^{-3}$ kg s$^{-1}$ m$^{-2}$); positive values are northward (into the page).

**Fig. 15.** Mean middle–upper-tropospheric (5–12 km AGL) along-line hydrometeor flux ($3 \times 10^{-3}$ kg s$^{-1}$ m$^{-2}$, with positive values northward), for the CS simulation. At each time, the averages are computed over the most intense 100-km segment of the convective line.
and Johnson 1995; Hilgendorf and Johnson 1998; Parker and Johnson 2000) and in models (e.g., Fig. 12c).

1) **Asymmetry in idealized simulations**

The TS/PS hybrids in Figs. 10a and 12c, in addition to those that will be discussed in Part II, bear great resemblance to the asymmetric TS MCSs discussed by Houze et al. (1990), Loehrer and Johnson (1995), and Hilgendorf and Johnson (1998). Such asymmetric structures have often been attributed to the cumulative impacts of Coriolis accelerations, or to the climatological distribution of high- \( \theta_e \) air in the central United States (e.g., as reviewed by Houze 2004). Neither of these explanations can be applied to the present idealized simulations, such that the behavior must be attributed to the wind profile. Trier et al. (1997) performed a case study simulation of an equatorial MCS using a fully 3D wind profile but no Coriolis accelerations; they too found that an asymmetric structure developed within the homogeneous model environment.

In large part, Trier et al. (1997) discussed this asymmetry in terms of the preferential strengthening of the line’s cyclonic, northern book-end vortex. Other studies (e.g., Davis and Weisman 1994; Skamarock et al. 1994; Weisman and Davis 1998) have also analyzed the symbiotic development of a predominant midlevel cyclonic mesoscale vortex and MCS asymmetries in the presence of Coriolis accelerations. Although the present paper is not primarily concerned with line-end vortices, the simulated PS system’s evolution toward asymmetry naturally raises the question of whether such vortices are present, and whether the preferential development of a cyclonic vortex is related to the system’s asymmetry in the 3D wind profile (without planetary rotation, as in Trier et al. 1997). In the CS simulation, line-end vortices do indeed slowly develop. The mesoscale low-midlevel winds are initially very symmetrical, which is not surprising because all of the line-parallel shear is above 3 km AGL. However, as the system matures and evolves through 6 h of simulation, it produces an anticyclonic southern line-end vortex that is actually stronger than its cyclonic northern vortex; the southern vortex’s 100 km \( \times \) 100 km areally averaged vorticity was between 7% and 22% greater in magnitude for every time examined. This was even more so the case in the control simulation.

Although a detailed vorticity budget is beyond the scope of the present article, it is clear that a predominant anticyclonic southern line-end vortex would not lead to the kinds of structures seen in Figs. 10a and 12c. In other words, the hybrid PS–TS precipitation structure develops in spite of the predominant southern anticyclonic vortex. In PS MCS simulations that include planetary rotation (Part II), more pronounced cyclonic vortices do indeed develop. However, they only intensify dramatically once the production of trailing precipitation is already underway, when convergence of planetary vorticity is focused beneath the stratiform heating in the large trailing anvil. In short, the cyclonic vortex in the with-Coriolis simulations is still largely a symptom of the evolution from PS to TS structure; and, based upon the no-Coriolis simulations, it is clearly not an essential ingredient for the evolution. Further investigation of the vortices themselves is set aside for future investigators.

As described above, the pathway to asymmetry in the present simulations is that, first, line-parallel precipitation develops, and then second, line-trailing precipitation develops. In this regard, the presence of along-line shear alone is sufficient to explain the basic evolution toward an asymmetric MCS structure. Perhaps the combination of line-perpendicular and line-parallel shear used in the present simulations is common enough to account for many midlatitude MCSs’ observed evolution toward asymmetry, much as suggested by Hilgendorf and Johnson (1998).

2) **Seeding of other cells**

The discussion to this point has emphasized one unique aspect of PS MCSs: their upper-level along-line flow fields advect hydrometeors downstream above the outflow boundary. As a result, newly developing convective updrafts are seeded by hydrometeors that were produced by other cells farther up the line (i.e., to the south). Idealized trajectories for the snow, graupel, and rain hydrometeor categories are depicted in Fig. 16. Although the Lin et al. (1983) microphysics scheme does not literally track individual droplets and crystals, trajectories that represent the 3D wind field and mass-weighted fall speeds of each hydrometeor category are representative of the general fallout patterns. The overall picture is of rain and graupel particles that fall out very close to where they were generated (Fig. 16); rain exists only in the lower troposphere, and graupel has a relatively large terminal velocity. However, snow has a fairly small fall speed and is primarily found aloft in regions where the line-parallel flow is significant. As a result, it can be advected large distances along the line.

Therefore, the advection of snow is of prime importance to the development of the PS region in the simulations. Of additional interest, however, is the ability of these snow particles to fall into newly developing updrafts (Fig. 16, thick gray trajectories). In the real world, introduction of already-grown snow into a fresh
updraft clearly can accelerate the production of precipitation (the seeder-feeder mechanism) through both vapor deposition and accretion. In the Lin et al. (1983) scheme this is represented through 1) increases in the rate of the snow growth through the parameterized Bergeron process and through accretion of cloud water and cloud ice and 2) increases in the rate of graupel growth through the parameterized autoconversion of snow and through accretion of rain and snow. In addition, rain develops more rapidly as the falling seeded snow melts. Many of the details of the parameterized seeder-feeder process were described for a similar microphysical scheme by Rutledge and Hobbs (1983).

Beyond the above microphysical effects, a seeded updraft will more rapidly experience the reversal to negative buoyancy due to hydrometeor loading and chilling from melting. A sensitivity test compared the development of an isolated updraft (from a single warm bubble) in a pristine environment to development in an environment with 1.4 g kg\(^{-1}\) of snow\(^8\) falling from between 6 and 11.5 km AGL. The presence of the seeding snow accelerated the onset of surface precipitation by about 1 min, and increased the peak surface rainfall rate by roughly 14%. As a result, the snow-seeded experiment produced a much stronger surface outflow than the pristine updraft experiment: after 40 min, the cold pool was 0.7 K colder (\(-7.5\) K versus \(-6.8\) K), very slightly larger, and had a surface pressure perturbation that was 34% greater (1.45 hPa versus 1.08 hPa) due to its increased depth. In section 4 it was suggested that the along-line motion of hydrometeors in the PS structure can lead to rapid intensification of the surface cold pool. The above, more detailed examination suggests that the along-line advection of snow is of prime importance to this intensification. In reality, the seeding process likely involves multiple hydrometeor species of various sizes; but, the involved hydrometeors need to be present in the upper-tropospheric along-line flow field, and need to have sufficiently small fall speeds that they can fall into developing updrafts farther down the line.

3) **UPDRAFT SURVIVAL AND INFLOW DESTABILIZATION**

Finally, it becomes clearer why the along-line advection of hydrometeors does not overwhelm developing updrafts farther down the line. Because most of the along-line transport comprises snow, with low density and fall speed, drag from the particles that fall into active updrafts does not hinder their development much. As well, given that the simulated PS MCSs begin by producing line-leading precipitation, it is also of interest to document the possible impacts of this line-leading precipitation upon the storms’ inflow. Just as described by Parker and Johnson (2004b) for simulated convective lines with leading precipitation, the layer of environmental air beneath the melting level is destabilized as it flows through the preline precipitation (Fig. 17). Parker and Johnson (2004b) attributed this destabilization predominantly to the evaporation and melting of falling hydrometeors [much as envisioned by Mechem et al. (2002) and Knight et al. (2004)], but also to the forced ascent of the inflowing airstream (similar to the upstream conditioning described by Fovell 2002). Figure 17 represents a fairly extreme example in which a moist absolutely unstable layer (MAUL; Bryan and Fritsch 2000) develops in the preline environment.

\(^8\)This is in the 70th percentile of values observed within the simulated PS system’s anvil.
Therefore, as discussed by Parker and Johnson (2004b), the presence of preline precipitation can actually be beneficial to the maintenance of convection during the developing stages of the simulated PS systems.

c. Back-building mechanism

In addition to along-line hydrometeor fluxes, the other critical component in the development of the PS structure is back-building toward the right of the line’s inflow side (i.e., southward). Back-building also occurs in the CS simulation (Fig. 18), and its southward progress is more plainly evident than in the control simulation because it is not being offset by reorientation of the line. Animations and manual cell tracking reveal that individual updrafts move largely eastward in the CS simulation, but that once a cell has matured and begins to weaken, it is often followed by a newly developing cell to its south\(^9\) (Fig. 19). One result of this process is that the southern extent of the convective updrafts then also progresses southward (Figs. 18, 19).

Previous sections have framed this behavior in terms of the general northerly flow that prevails immediately behind the gust front in the simulated PS systems, and the southward advection of hydrometeors in the lower troposphere. In fact, a closer analysis reveals that each individual downdraft that contributes to the surface cold pool generally also entails a northerly surge in wind within the cold pool. Numerous such surges, with attendant gust fronts, are evident throughout the outflow at any given time (Fig. 20a). Indeed, it is these surges that lead to the scalloped shape of the main outflow boundary (Fig. 20a). The northerly gust fronts move southward at 10–15 m s\(^{-1}\), which is about the speed at which the system back-builds southward: in Fig. 18, the southern end of the line moves roughly 37 km in 1 h, for a speed of 10.3 m s\(^{-1}\).

Dynamically, the northerly flow associated with each downdraft pulse can be attributed to the along-line vertical wind shear (there is more on PS system’s dynamic

\(^9\) Some authors (e.g., Bluestein and Jain 1985) define back-building as new cells appearing “upstream, relative to cell motion” from older cells. Recall that, in the present experiments, the environmental wind profiles are cell-relative in order to keep the convection centered within the domain. If we add a constant to the entire wind profile to make it line-relative (i.e., the difference between the gray and black circles in Fig. 4), the cells in the simulations move northward along the line, such that the southward back-building also satisfies their definition.

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**Fig. 17.** Skew \(T\)-log \(p\) plot of temperature and mixing ratio for the base-state environmental sounding (heavy dotted curves) and the near-line sounding from \(t = 2:00\) in the CS simulation (taken from \(x = 283\) km, \(y = 275\) km; cf. Fig. 12a).

**Fig. 18.** Locations of lower-tropospheric updrafts (\(w > 5\) m s\(^{-1}\) at 2.5 km AGL; shaded) and reflectivity maxima (dBZ > 40; contoured) for the CS simulation at \(t = 1\) h (left side) and \(t = 2\) h (right side). The two panels show the same area, one hour apart.
pressure gradient accelerations in Part II). Downdrafts in the presence of southerly along-line shear experience southward along-line accelerations, leading to the structures seen in Fig. 20a. This process works best when there is along-line shear extending all the way to the surface. As a result, the control simulation exhibits more significant back-building than the CS simulation (not shown), although in the control run there exist the aforementioned complications due to reorientation of the convective line in time. Even so, the generation of northerly outflow surges is still significant in the CS wind profile. The intersections between these northerly gust fronts and the main outflow boundary are regions that favor new development because the lifting associated with the two features are superposed. Upward velocities are maximized above the northerly gust fronts (Fig. 20b). As well, the cold pool is deeper in these areas due to convergence (Fig. 20b), and this in turn provides for deeper lifting along the main north–south outflow boundary.

Animations reveal that all of the northerly gust fronts move southward within the cold pool. As a result, the favored regions of new convective development move southward in time. In other words, a new cell “n,” will most likely occur to the south of its immediate predecessor, “n – 1,” in a storm-relative sense, because it is most likely to develop along the intersection of the main outflow boundary and the northerly gust front of “n – 1.” The convective-scale mechanism is the explanation for why along-line vertical wind shear entails back-building, such as exhibited by PS systems. In nature, other mechanisms related to inhomogeneous mesoscale environments may also explain back-building. However, the present mechanism is robust, dynamically consistent, and has been observed informally by the author and collaborators on numerous occasions.

6. Conclusions

By combining conventional data from an observed case with idealized numerical simulations, this article provides what may be the first consolidated physical
depiction of the convective lines with parallel stratiform (PS) precipitation that develop in environments with both line-perpendicular and line-parallel vertical wind shear. It is notable that many linear convective systems initiated along fronts will experience such wind profiles (provided the fronts are near thermal wind balance). Hence, PS systems are somewhat common to the mid-latitudes (PJ00). This study reveals the following prominent features:

- In the characteristic 3D wind profiles, lower-tropospheric storm-relative hydrometeor advection and outflow expansion toward the line’s right (south in the simulations) produces back-building on both the mesoscale and the convective scale. At the same time, upper-tropospheric storm-relative hydrometeor advection toward the line’s left (north in the simulations) produces a line-parallel precipitation region. These behaviors together combine to bring about the characteristic PS structure.

- The line-leading and trailing anvils are the sites of the most significant along-line hydrometeor transports in the mature PS structure. Precipitation that falls on the line’s leading side can destabilize the system’s inflow.

- Because precipitation particles move primarily along their convective lines, PS systems produce most of their outflow in very close proximity to the surface outflow boundary. In addition, their convective cells can seed one another. As a result, their cold pools strengthen quite rapidly.

- The intensifying outflow, along with diminishing line-parallel flow within the line’s axis, implies that such systems will commonly evolve toward a trailing precipitation structure in time. As a result, the 3D environmental wind profile yields a realistic-looking asymmetric MCS structure even in the absence of Coriolis accelerations and environmental inhomogeneities.

Within the basic structure described in this paper, the dynamics that lead to the along-line velocities of convection-processed air parcels are of prime interest. In the companion paper, these governing dynamics and their sensitivities to the environment, and to the configuration of the numerical model, are investigated in detail.

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