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The Initiation and Evolution of Multiple Modes of Convection within a Meso-Alpha-Scale Region

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ABSTRACT

On 30 March 2006, a convective episode occurred featuring isolated supercells, a mesoscale convective system (MCS) with parallel stratiform (PS) precipitation, and an MCS with leading stratiform (LS) precipitation. These three distinct convective modes occurred simultaneously across the same region in eastern Kansas. To better understand the mechanisms that govern such events, this study examined the 30 March 2006 episode through a combination of an observation-based case study and numerical simulations. The convective mode was found to be very sensitive to both the environmental thermodynamic and wind shear profiles, with variations in either leading to different convective modes within the numerical simulations. Strong vertical shear and moderate instability led to the development of supercells in western Oklahoma. Strong shear oriented parallel to a surface dryline, coupled with dry air in the middle and upper levels, led to the development of the PS linear MCS in central Kansas. Meanwhile, moderate wind shear coupled with high instability and strong linear forcing led to the development of the LS MCS in eastern Kansas. Absent linear forcing, the moderate shear environment in eastern Kansas was supportive of isolated supercells in the numerical experiments. This suggests that the linear initiation mechanism was key to the development of the LS linear MCS. From the results of this study it is conceded that, for this event, localized environmental variations were largely responsible for the eventual convective mode, with the method of storm initiation having an impact only within the weaker shear environment of eastern Kansas.

1. Introduction

A principal element of a severe weather forecast is the determination of the organizational structure, or mode, that the convective storms will take after initiation. Past literature has defined convective mode in a variety of ways, generally dealing with the organizational characteristics of convective storms (e.g., Bluestein and Jain 1985; Bluestein and Parker 1993; Parker and Johnson 2000; Kain et al. 2006). For the purposes of this paper we define convective mode as the meso-beta-scale organizational characteristics of a convective storm. In this vein, we will be discussing four distinct convective modes: supercell thunderstorms, linear mesoscale convective systems (MCS) with trailing stratiform precipitation (hereafter TS), linear MCSs with leading stratiform precipitation (hereafter LS), and linear MCSs with parallel stratiform precipitation (hereafter PS). Properly anticipating the convective mode is important because different modes tend to be associated with different severe weather threats (Johns and Doswell 1992; Doswell and Evans 2003; Kain et al. 2006). In general, supercell storms tend to produce tornadoes, hail, and severe winds (e.g., Doswell and Burgess 1993; Davies-Jones et al. 2001), while linear modes, specifically bow echoes, tend to favor damaging straight-line winds (e.g., Fujita 1978; Przybylinski 1995; Wakimoto 2001). In addition, PS and LS MCSs can present a larger flash flooding threat due to either their slower motion [for LS systems, e.g., Pettet and Johnson (2003)] or their training of cells over one area [for PS systems, e.g., Parker and Johnson (2000); Schumacher and Johnson (2005)]. The type of severe weather threat may even vary significantly among MCS modes (Gallus et al. 2008). Given these associations between storm mode and hazardous weather threats, an accurate prediction of the mode can lead to better situational awareness and more effective outlooks and warnings (McNulty 1995).

However, despite its importance in the formulation...
of an accurate severe weather forecast, the convective mode remains difficult to anticipate and is an area of continuing research and focus (Kain et al. 2006). In line with past research, forecasters generally rely on an analysis of vertical wind shear to anticipate the convective mode (Johns and Doswell 1992; McNulty 1995; Moller 2001; Edwards et al. 2002). This approach, however, can become complicated as supercells, bow echoes, LS MCSs, and PS MCSs are all known to occur within moderate-to-high wind shear environments (e.g., Bluestein and Jain 1985; Bluestein and Weisman 2000; Doswell and Evans 2003; Parker and Johnson 2004a; Parker 2007a,b). It becomes complicated further in cases where two or more of these modes are present at the same time. Past climatological studies (e.g., Dial and Racy 2004; Bunkers et al. 2006) have indicated that while not as common as single-mode events, multimode events do happen frequently enough to be of concern. One such event occurred on 30 March 2006 and is the focus of this study. This event featured isolated supercells, as well as linear MCSs with parallel and leading stratiform precipitation evolving simultaneously over eastern Kansas (Fig. 1).

In light of the complex and varied severe weather threat associated with these multimode events, the specific aim of this study is to examine the mechanisms behind one such event, both in terms of storm initiation (initial storm development within the first 30–60 min) and subsequent storm evolution. This effort is relevant to the forecasting problems of (a) predicting the initial severe weather threat based on how storms will organize upon initiation and (b) predicting how that threat will change over time as storm organization evolves. Our long-range goal is to identify and understand the key features that favor specific modes within larger-scale moderate-to-high shear environments.

**Background**

Much past research has focused on vertical wind shear as a key factor in the determination of the con-
vective mode, with many studies (dating back to Hane 1973; Thorpe et al. 1982; Weisman and Klemp 1982; Seitter and Kuo 1983) utilizing idealized model simulations as their tool of choice. Weisman and Klemp (1982) found an increase in storm organization with increasing shear, as isolated ordinary cell thunderstorms were favored in environments with no vertical shear, multicell storms in environments with low-to-moderate shears, and supercells in environments with moderate-to-high wind shears. Weisman and Klemp (1984) further determined that clockwise-turning hodographs favored right-moving supercells over left-movers. Also, for cases of moderate shear, their simulations produced a system with supercellular structures favored on the right flank of the system and multicells on the left flank, not unlike the observed cases of a supercell storm at the southern end of a squall line. This suggests that wind shear is a strong determinant of the convective mode for high or low values but is less decisive for moderate-range values, where both multicell and supercell structures are possible.

The orientation of both the low-level (0–3 km) and deep-layer (0–6 km) shear vectors with respect to a storm’s cold pool can also be important in determining the organizational mode that a linear MCS will take (Parker and Johnson 2004b; Parker 2007b). For LS and TS MCSs, the deep-layer shear vector is predominantly oriented perpendicular to the convective line, with the key difference being that the magnitude of the shear vector is greater for the LS environment (Parker and Johnson 2004b). In the case of linear MCSs with parallel stratiform precipitation, the environment typically possesses line-perpendicular shear in the low levels and line-parallel shear in the middle and upper troposphere [i.e., 3–10 km; Parker (2007a)]. Parker and Johnson (2004a) showed that the environments for LS systems and supercells overlap, and Parker (2007a,b) noted that the environments for PS systems and supercells overlap (Fig. 2). A similar overlap in environments has been identified for supercells and particularly strong TS systems as well (Doswell and Evans 2003). In other words, environments with moderate (10–20 m s$^{-1}$) to strong (>20 m s$^{-1}$) vertical wind shear may permit four distinguishable primary structures.

Within such moderate-to-high shear regimes, the arrangement of linear surface boundaries may then be important. Bluestein and Jain (1985) observed both supercells and backbuilding squall lines forming in similar environments, and in similar proximity to surface boundaries. They hypothesized that the orientation of the vertical shear with respect to the boundary may have been relevant to the convective mode. To this end, Bluestein and Weisman (2000) examined the effects of varying the wind shear angle with respect to a line of forcing (in their case a dryline) on numerically simulated supercells. In their simulations, curved hodographs supportive of supercells were used in every case; however, the ultimate mode varied considerably based on the orientation of the vertical shear with respect to the simulated dryline. For shear perpendicular to the boundary, their simulations generated a squall line with right- and left-moving supercells at either end. For shear oblique to the boundary, the result was a line of isolated (i.e., not interacting) right-moving supercells. Finally, for shear parallel to the line, the longest-lived storms were observed at the downshear end of the line of forcing. These storms consisted of a right-moving supercell and a left-moving storm that
exhibited multicell characteristics (Bluestein and Weisman 2000).

Dial and Racy (2004) further examined the role of synoptic boundaries in determining the convective mode. The authors determined that when the 2–6- or 2–8-km flow and a boundary were nearly parallel, the result was a rapid transition to a more linear mode due to mergers and interactions between storms being aided by the mean flow. This flow parallel to the boundary can also advect hydrometeors along the line, seeding new updrafts and aiding in the production of precipitation (Parker 2007a). This, in turn, can lead to stronger cold pool development and favor linear modes. It is also important to note that boundaries can have relevance to the convective mode well past the initial development of the storms. Jewett and Wilhelmson (2006) found that the inclusion of a simulated cold front in idealized squall-line simulations had a significant effect on storm structure, causing noticeable differences in individual cell behaviors and the overall storm intensity when compared to control simulations without the cold front.

While the majority of the findings discussed thus far deal with how a storm initially organizes within a particular shear environment, Richardson et al. (2007) showed that variations in environmental shear during the course of a storm’s lifetime may have an impact on its organization as well. Using idealized numerical simulations with horizontally varying vertical wind shear, the authors found that storms became increasingly organized as they moved into a region with stronger vertical shear. This would suggest that it is not just a storm’s initial environment that is important to its organizational mode, but also the environment into which it is moving.

Finally, while much of the work discussed thus far has dealt in some way with the role of wind shear in determining the mode, thermodynamic factors, such as the buoyancy and moisture profiles, can play a role as well. Dry air in the lower and middle levels of the atmosphere can enhance cold pool development through evaporational cooling, leading to colder, broader cold pools that favor slabular lifting and linear modes (James et al. 2006). Dry air aloft has also been shown to have an effect on supercell thunderstorms, helping to enhance downdrafts and creating strong surface outflow that can be detrimental to mesocyclone and storm longevity (Gilmore and Wicker 1998; McCaul and Coen 2002).

In short, a review of past work shows a variety of factors that can influence the convective mode, with vertical wind shear being of primary importance. However, while its importance is evident, the usefulness of shear in delineating between convective modes may be limited in moderate-to-high shear environments, wherein a variety of modes have been observed. Additionally, a majority of the works discussed have tended to focus on single modes of convection, evaluating only supercells or only linear MCSs. As a result, there has been little examination of events that feature multiple modes of convection within a localized area. The present study will seek to address these issues utilizing the case of 30 March 2006, as it was a multimodal event that occurred within a moderate-to-high shear environment. This case will serve as the basis for an observational case study as well as subsequent numerical simulations.

Section 2 details the results of the observed case study, setting the stage for the numerical simulations, which are discussed in section 3. Section 4 then synthesizes the results of the case study and simulations, revisiting the broader theme of multiple modes of convective storms in a localized region and suggesting some possible avenues for future work.

2. Observed case

a. Case study methodology

The observational case study made primary use of data available from operational platforms. The background synoptic conditions for this case were determined from isobaric charts and skew T–logp plots generated from radiosonde observations from the operational observing network, including special 1800 UTC radiosonde observations taken across the region (Fig. 3). Regional Automated Service Observing System (ASOS) surface observations were used to identify surface features and Weather Surveillance Radar-1988 Doppler (WSR-88D) data from Wichita, Kansas (KICT); Topeka, Kansas (KTWX); Vance Air Force Base, Oklahoma (KVNX); and Kansas City, Missouri (KEAX), provided base reflectivity and Doppler velocity observations covering the scope of the event (Fig. 3). Finally, the radiosonde wind profiles were supplemented by hourly observations from a regional National Oceanic and Atmospheric Administration (NOAA) wind profiler site (Fig. 3).

These observations were supplemented by data from two gridded datasets: the North American Regional Reanalysis (NARR; Mesinger et al. 2006) and archived mesoanalyses combining Rapid Update Cycle (RUC) model output and real-time observations, created by the Storm Prediction Center (SPC) in Norman, Oklahoma (SPC mesoanalyses; Bothwell et al. 2002). The NARR data were selected to provide enhanced cover-
age both spatially (32-km horizontal grid with 45 vertical layers) and temporally (analyses every 3 h), allowing for a more complete picture of the event, especially in the vertical. Meanwhile, the SPC mesoanalyses provided a variety of sounding-derived severe weather parameters in plan view at hourly intervals. Because these data are used operationally by both the SPC and local National Weather Service forecast offices, we considered them to be a useful and relevant tool for this study.

To ensure accuracy, the NARR data were compared to available observed data at both 1200 and 1800 UTC on 30 March as well as 0000 UTC on 31 March. In general, the NARR was found to be representative of regional soundings and surface observations, especially east of the dryline. The one apparent weak point in the NARR data was its representation of the air mass behind the dryline, where the NARR was too moist throughout the profile. The parameters chosen from the SPC mesoanalyses were compared to those computed from 1800 UTC radiosonde observations within the region and were generally found to be similar.

To develop a three-dimensional picture of the environment, it was of interest to obtain vertical wind and thermodynamic profiles characteristic of the prestorm environments for each mode. These were readily available for the supercells and the LS line, using the 1800 UTC Lamont, Oklahoma, and Topeka, Kansas, radiosonde observations, respectively. However, there was no readily available radiosonde observation within the vicinity of the location of the PS line formation. While the NARR data provided a possible avenue to fill this data void, its apparently poor representation of the air mass west of the dryline was a significant concern. As a test, a NARR sounding representative of the time and region where the PS line formed was compared to the 0000 UTC 31 March Topeka radiosonde observation, launched just ahead of the dryline approximately 6 h later. The observed profile was again considerably drier aloft than the NARR data, reiterating that the NARR was too moist. We concluded that the 0000 UTC Topeka observation was more representative of the pre-dryline environment. As a result, a composite sounding was created using the 0000 UTC 31 March Topeka radiosonde observation; the 1800 UTC 30 March Salina, Kansas, surface observation; and the 1800 UTC Fairbury, Nebraska, wind profile. The 1800 UTC Salina surface observation and the Fairbury wind profile were of interest as they represented the nearest observations of their type at the time of storm initiation. Combined, the composite of these three features (hereafter TSF) likely represents a close approximation of the environment present in central Kansas where the PS line originated on 30 March 2006.

In this study we focused on a single case rather than multiple cases in order to emphasize a detailed analysis of each of the individual storms and the small-scale environmental features across the region, which might be otherwise lost within a more limited parameter study over a larger number of cases. The 30 March 2006 case presents a rather unique opportunity to examine three distinct modes of convection in one general synoptic-scale regime, allowing us to focus on the mesoscale features that were key in mode delineation.

b. Case study results

The case of 30 March 2006 included three distinct modes (see definition at the beginning of section 1) of convection shown in Fig. 1: an MCS with parallel stratiform precipitation (hereafter PS line) in east-central Kansas, an MCS with leading stratiform precipitation...
ation (hereafter LS line) in far eastern Kansas, and a group of isolated supercells between these lines in eastern Kansas. All three remained present for 2–3 h within an area of less than 400 km × 500 km. During the course of this event the storms affected central and eastern Kansas, most of northern Oklahoma, and parts of western Missouri.

1) BACKGROUND ENVIRONMENT

Key features of the prestorm synoptic environment are summarized in Fig. 4. A 50 m s$^{-1}$ jet streak (Fig. 4a) and upper-level trough (Figs. 4a and 4b) over the southwestern United States, along with low-level warm advection (Fig. 4c), provided synoptic-scale lift across the
southern plains. A southwesterly 25 m s\(^{-1}\) low-level jet was transporting warm moist air into Oklahoma and Kansas (Fig. 4c) helping to destabilize the atmosphere ahead of an advancing surface dryline (Fig. 5). This destabilization was evident in the 1800 UTC upper-air soundings from around the region, which indicated a moderately unstable [100-mb mixed layer convective available potential energy (MLCAPE\(^2\)] of approximately 1000–2000 J kg\(^{-1}\), weakly capped environment to the east of the dryline (Fig. 6). In addition, moderate (10–20 m s\(^{-1}\)) to strong (>20 m s\(^{-1}\)) vertical wind shear (Fig. 7) suggested supercell or squall-line organization was possible (Rasmussen and Blanchard 1998; Evans and Doswell 2001).

2) RADAR ANALYSIS

The isolated supercells on 30 March 2006 were initiated along and just ahead of a surface dryline in western Oklahoma at approximately 1630 UTC (Fig. 8a). While the initial storms consisted of both isolated and broken linear structures, they quickly moved northeastward off of the dryline, becoming increasingly isolated in nature while intensifying and developing supercellular characteristics (Fig. 9a). By 1845 UTC, many of these storms had evolved into isolated supercells, featuring hook-echo and bounded weak echo region (BWER) reflectivity structures (Figs. 10a and 10c) as well as well-developed mesocyclones evident in Doppler velocity data (Fig. 10b). Additionally, numerous reports of severe hail greater than 2.54 cm (1.00 in.) in diameter, as well as several tornado reports, resulted from these storms. The isolated supercellular organization remained until dissipation in eastern Kansas and Oklahoma.

By approximately 1800 UTC, several cells were also initiated in close proximity to one another along the northern portion of the dryline in central Kansas (Fig. 8b). A few of these initially developed supercellular characteristics, with weak mesocyclones and hook-echo structures (Fig. 8b); however, the cells quickly merged into a small line, which then began backbuilding to the south along the dryline (Fig. 9b). This line matured into a linear MCS with parallel stratiform precipitation, having a narrow convective line extending north–south through central Kansas, and a region of stratiform precipitation located at the northern end of the line (Fig. 11a). Vertical cross sections in both the along- and across-line directions reveal substantial stratiform precipitation north of the strongest convection, parallel to the convective line (Fig. 11b), with little stratiform precipitation ahead of or behind the line (Fig. 11c). The PS system progressed eastward across Kansas, remaining just ahead of the surface dryline (evident as a fineline feature in the radar imagery and denoted by the scalloped line in Fig. 11a). Eventually, it evolved into a linear MCS with trailing stratiform precipitation (TS) by 2100 UTC (Fig. 9d), as is often observed with this convective mode (Parker and Johnson 2000; Parker 2007a). After the transition to the TS mode, the MCS began to weaken as it crossed northeastern Kansas and southeastern Nebraska, losing most of its organization by approximately 2330 UTC. During its lifespan, numerous reports of severe hail were associated with this MCS, especially early in its lifetime while some of the initial cells maintained supercellular characteristics. Severe winds were reported with this system after the transition to the TS mode in northeastern Kansas.

Meanwhile, just after 1900 UTC, as the supercells and PS line were evolving to the west, a new squall line (which would become the LS line) began rapidly developing just east of the supercells in eastern Kansas (Fig. 9b). Rather than being forced along the dryline, as was the case with the supercells and PS line, these storms appear to have been forced by a collision between two outflow boundaries. Surface observations in this area were sparse; however, earlier observations in the vicinity of the supercells recorded temperature drops of 6°C within the storms and 2–3°C near their periphery, suggesting at least some weak outflow from these storms. Observations to the east also show small (1°C) temperature falls that followed the passage of earlier convection (visible near KTWX in Fig. 9a). The strongest evidence of this outflow collision, though, can be seen in the radar data, which show two finelines, indicative of boundaries that appeared to merge as this line developed (Fig. 12). Following the merger, a squall line rapidly developed and eventually produced leading stratiform precipitation (Fig. 13a). A line-perpendicular cross section at 2103 UTC shows two key elements of the front-fed LS structure discussed by Parker and Johnson (2004b): the leading stratiform region in the reflectivity field (Fig. 13b), as well as the characteristic preline structure of low-level flow toward the convective line, with mid- and upper-level flow away from the convective line (Fig. 13c). Unlike the supercells and PS MCS, the LS line produced very little in the way of severe weather, with only some very widely scattered reports of severe hail during its lifetime. There were also no reports of flooding with this MCS, as is sometimes observed with this organizational mode. This

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\(^2\) MLCAPE is chosen because past research has demonstrated that using a mean mixed layer parcel provides a better estimation of the lifting condensation level height, and thus CAPE, compared to a surface-based parcel (Craven et al. 2002).
is likely because this LS MCS was a front-fed LS MCS, whereas the slower-moving, flash-flood-causing LS MCSs studied by Pettet and Johnson (2003) were of the rear-fed (ingesting inflow from behind the convective line) variety. The storm maintained its leading stratiform structure as it moved eastward into Missouri, where it eventually began dissipating by 2230 UTC.

c. Initiation mechanisms

The aim of this study was to understand the mechanisms that led to these three distinct convective modes within the same area on 30 March 2006. While all three modes ultimately ended up in close proximity to one another, they were initiated in different areas, by two different forcing mechanisms: a sur-
face dryline and a collision between two outflow boundaries.

The dryline provided a mesoscale linear forcing mechanism, evident as a maximum in surface convergence along the length dryline, from which one can infer upward vertical motion (Fig. 14). Convergence was maximized in central Kansas where the PS line formed. Linear forcing from the dryline initiated a number of storms in close proximity, leading to mergers and upscale development into the PS MCS. Weaker convergence extended along the dryline to the south into Oklahoma, resulting in the formation of a multicell line along the boundary (Fig. 8a). In this region, though, the environment favored storm motion away from the dryline, and as such the initial line evolved into isolated supercells as it moved away from the lin-
ear forcing (Figs. 9b and 9c). The environmental features making this possible will be discussed in the next section.

A linear forcing mechanism was also responsible for the development of the LS line in eastern Kansas. In this case, it was a collision between two outflow boundaries that provided the forcing. The colliding outflows provide a more slabular (James et al. 2005) source of lifting, initiating storms in a broad swath of convection rather than as individual cells (Fig. 12). This slabular lifting would tend to favor linear modes and was likely a key component in the development of the LS line.

d. Environmental variations

In addition to these variations in storm initiation, localized environmental inhomogeneities may have been a factor in this event as well, both in the initiation...
of the individual modes, as well as during their subsequent evolution. Because the supercells and PS line both developed along the dryline, we first focus on key differences between the local environments of these two modes. We then examine the environment in eastern Kansas where the LS line formed.

One important difference between the supercell and PS environments is a variation in the direction of the midlevel winds with respect to the dryline depicted in Fig. 15a. To the south, across Oklahoma, southwesterly midlevel winds resulted in a more across-dryline flow, allowing initial cells to move off the boundary, and favoring more isolated organization (i.e., the supercells; Fig. 9b). However, to the north, they were more southerly and nearly parallel to the dryline, causing the initial storms to remain close to the linear forcing of the dryline (Fig. 11a). Given that a linear forcing mechanism would tend to favor linear organization, prolonged residence near such a forcing would aid in the development of a linear mode such as the observed PS line.

This variation in the midlevel winds also corresponded to a north–south variation in the orientation of the 0–6-km shear vectors (Fig. 16a). To the south, where the supercells formed, the 0–6-km shear was oriented at approximately a 45° angle from the dryline, limiting cell interactions and favoring isolated development (Bluestein and Weisman 2000). Farther north, where the PS line formed, the 0–6-km shear was more nearly parallel to the dryline, favoring cell mergers (which were observed in radar animations from 30 March) and thus linear modes (Bluestein and Weisman 2000; Finley et al. 2001). Additionally, along-line shear can further favor linear development through the seeding of hydrometers into downstream cells aloft, expediting cold pool development, and leading to a strong, broad cold pool (e.g., Dial and Racy 2004; Parker 2007a). While there were no observations of fine enough scale to determine specific hydrometeor motions, the formation of a region of parallel stratiform precipitation suggests it is likely that seeding occurred, much as was seen in the PS simulations of Parker (2007a,b).

In addition to the north–south variation in the direction of the 0–6-km shear vector, the NARR data and archived SPC mesoanalyses suggest a variation in the

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3 To be exact, the idealized simulations of Bluestein and Weisman (2000) featured long-lived right-moving storms, with left-moving storms that weakened as they moved back over the cold pools of neighboring storms when the wind shear was oriented 45° to their simulated dryline. Left-moving storms were not observed in this case, likely because this particular environment featured a strongly curved hodograph (Fig. 7c), which overwhelmingly favored the right-moving storms.
magnitude of the shear as well. As discussed previously, available observations representative of the super-cell and PS line environments (taken at Lamont, Oklahoma, and Fairbury, Nebraska, respectively) provide similar shear magnitudes of approximately 25 m s$^{-1}$. However, given that these were point observations spatially removed from where the storms were initiated, we deemed it useful to examine the more spatially expansive NARR and mesoanalysis data. Indeed, the gridded datasets suggest that there was slightly weaker shear (20–25 m s$^{-1}$) along the dryline in central Kansas, and slightly stronger shear (25–30 m s$^{-1}$) farther south in Oklahoma (Fig. 16a). Thus, in addition to the variations in shear direction, the development of two different modes of convection along the dryline may have also been aided by a variation in the overall magnitude of the vertical shear, with stronger shear further favoring supercells to the

Fig. 9. Evolution of all three modes during the course of the 30 Mar 2006 event as depicted by radar reflectivities at (a) 1802 UTC for KICT, (b) 1902 UTC for KICT, (c) 2001 UTC for KICT, and (d) 2159 UTC for KTWX. The three convective modes are labeled for reference.
south, and slightly weaker shear favoring the PS line to the north.

Complementing the 0–6-km shear analysis, an analysis of the 0–3-km storm-relative helicity (SRH) shows large values (>200 m² s⁻²) all along the dryline, with a maximum greater than 300 m² s⁻² in central Oklahoma (Fig. 16a). Past research (e.g., Davies-Jones 1984; Rasmussen and Blanchard 1998; Thompson et al. 2003) indicates that the SRH > 200 m² s⁻² along the length of the dryline was sufficient for supercells. However, the greater SRH to the south would suggest an even more strongly clockwise-curved hodograph, resulting in a greater likelihood of right-moving supercells. In fact, as the initial storms that developed in Oklahoma moved off of the dryline, they moved into this region of enhanced SRH and evolved into supercells (Figs. 9b and 9c). Thus, the strong 0–3-km SRH in northern Oklahoma likely helped the development of the isolated supercells observed in this case.

From a thermodynamic perspective, there was little variation along the dryline in terms of instability, with MLCAPE values of approximately 1500 J kg⁻¹ present across central Oklahoma and Kansas east of the dryline (Fig. 17a). A more significant thermodynamic difference between these two environments was the presence of drier air aloft to the north where the PS line formed.
This is shown quite dramatically as an intrusion of drier air over Kansas in a north–south cross section created from the 1800 UTC NARR data (Fig. 18). A region of very dry air at the surface extending from western Kansas southwest into New Mexico at 1800 UTC (Fig. 5) is likely the surface indication of this elevated zone of dry air, with deep mixing bringing the drier air down to the surface behind the dryline. The elevated layer of dry air is also evident in the 0000 UTC Topeka radiosonde observation, upon which the TSF sounding was based (Fig. 6a). This observation was taken just ahead of the dryline, suggesting a similar environment would have been present ahead of the dryline in west-central Kansas 6 h earlier.

The presence of dry air aloft in the region where the PS line formed is significant, as dry air can enhance cold pool development due to evaporational cooling (e.g., James et al. 2006). This would favor the development of linear modes as stronger cold pools would tend to spread and interact, resulting in a broad region of lifting along the leading edge of the cold pool. While a paucity of surface observations precluded a quantitative analysis of the cold pool’s relative strengths, there is some qualitative evidence that the cold pool associated with the PS line was larger and stronger than those associated with the supercells. Several surface observations from Salina (KSLN in Fig. 3) between 1300 and 1400 UTC recorded a sustained temperature and pressure perturbation associated with the PS line. Meanwhile, observations taken farther south, in the vicinity of the supercells (KEWK, KICT, and KIAB in Fig. 3), recorded more fleeting temperature perturbations and no pressure perturbations. These observations suggest, at least qualitatively, that the dry air aloft farther to the north aided in the development of a large, strong cold pool, favoring the observed linear mode. To the south, the lack of dry air apparently resulted in weaker, smaller cold pools, limiting linear organization and thus aiding in the maintenance of the observed isolated supercells.
While thus far the discussion of the environmental variations has focused on the dryline region, the third environment well east of the dryline in eastern Kansas was important in the formation of the LS line. This environment differed from those associated with the supercells and PS line in two key ways: it possessed weaker vertical wind shear and more convective inhibition. The environments that spawned the supercells and PS MCS were both characterized by high 0–6-km shear vector magnitudes of approximately 25 and 20 m s$^{-1}$, respectively. However, the environment over eastern Kansas, characterized by the 1800 UTC Topeka radiosonde observation, contained a more modest 0–6-km shear vector magnitude of approximately 16–18 m s$^{-1}$ (Fig. 7b, and 16a). This resulted in an environment capable of sustaining both multicell and supercell storms [as documented in the simulations of Weisman and Klemp (1984)]. In addition, while the environment

![Fig. 12. Base reflectivity data from KICT for 1853–1919 UTC, showing the development of the LS MCS due to a collision of outflow boundaries. Inferred outflow boundaries are denoted by black lines.](image)
along the dryline was characterized by moderate instability (MLCAPE approximately 1000–1500 J kg\(^{-1}\)) and little convective inhibition (MLCIN < 10 J kg\(^{-1}\); Figs. 6a and 6c), the eastern Kansas environment featured a similar amount of instability (1109 J kg\(^{-1}\) of MLCAPE) but more convective inhibition (MLCIN = −88 J kg\(^{-1}\); Fig. 6b). These two features meant that the forcing mechanism for the LS line played a significant role in its development.

As discussed previously, the key to the LS line’s development appears to be the linear forcing from an outflow collision (Fig. 12). This forcing was key to the development of the LS line in two ways. First, given the stronger convective inhibition in this region, the strong forcing from the outflow collision may have been necessary to lift parcels to their level of free convection (LFC) and initiate the storms that would become the LS line. Without the strong forcing mechanism, the LS line may not have been able to develop due to the strong convective inhibition (CIN). Second, the overall weaker shear made the environment less favorable for supercells, thus emphasizing the role of the linear lifting in determining the organizational mode. And while weaker, the shear vectors in eastern Kansas were oriented across the initial convective line (the southwestern shear in eastern Kansas in Fig. 16a), favoring LS development (Parker and Johnson 2004b). Thus, once the squall line formed due to the outflow collision, the environmental shear helped to organize it into the LS mode.

While these environmental inhomogeneities were evident, and significant, during the developmental phase of the three different modes of convection on 30 March 2006, the progressive upper-level pattern ensured that these features did not remain static throughout the event. By 2100 UTC, several key features had evolved along with the larger-scale pattern. Most notably, both the 0–6-km wind shear and 0–3-km SRH had

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**Fig. 13.** LS line radar analysis from KTWX and KEAX at 2104 UTC 30 Mar 2006. (a) Plan view of base reflectivity from KTWX focused on the LS line. (b) Reflectivity cross section from KEAX taken across the LS line following line A–a in (a). (c) As in (b) except with radial velocity. The characteristic LS airflow is denoted by the arrow in (c).
increased across central and eastern Kansas. By this
time, the majority of the region of interest east of the
dryline contained 0–6-km wind shear of 25–30 m s\(^{-1}\)
as well as 0–3-km SRH values of >300 m\(^2\) s\(^{-2}\) (Fig. 16b).
The increase in both of these fields across central and
eastern Kansas may have enhanced the longevity of the
isolated supercells as they moved into this region ahead
of the PS line throughout the afternoon, with most of
the storms remaining isolated and exhibiting supercell
characteristics until their dissipation. Additionally, as
the 0–6-km shear increased, it continued to be oriented
nearly parallel to the dryline toward the northern end
of the line. This prolonged, strong, line-parallel shear
resulted in the maintenance of a favorable environment
for the PS line just ahead of the dryline as the afternoon
progressed. MLCAPE values ahead of the dryline re-
maind greater than 1500 J kg\(^{-1}\), providing sufficient
instability for storm maintenance (Fig. 17b).

One key feature that did not change very dramati-
cally during the course of the afternoon was the direc-
tion of the midlevel winds just ahead of the dryline (Fig.
15b). As the dryline advanced eastward, the eastward
progress of the upper-level trough maintained a strong
southerly component to the midlevel winds along and
east of the dryline. This precluded the PS line from
moving off the dryline. The continued proximity to the
linear forcing of the dryline may have helped sustain
the linear mode of the PS line, with the line-parallel
winds maintaining the parallel stratiform organization.

The observational case study suggests that the pro-
duction of the various modes was the result of both
variations in storm initiation mechanism (dryline versus
outflow collision) and localized environmental inhomoge-
neities. The maintenance of these distinct modes was
then further aided by the favorable evolution of several
environmental parameters as the event progressed.
These hypotheses cannot be completely examined us-
ing just observations, and thus they were tested through
the use of numerical simulations, which will be dis-
cussed next.

3. Model simulations

To test the hypotheses outlined in the previous sec-
tion, we devised experiments using idealized numerical
simulations. These controlled simulations enabled us to
isolate the possible roles of the varying environmental

FIG. 15. Midlevel wind analysis using NARR data from 30 Mar 2006. (a) The 500-hPa v-wind com-
ponent (contours, m s\(^{-1}\)) and total wind (barbs) at 1800 UTC. (b) As in (a) but at 2100 UTC. Barbs are
in m s\(^{-1}\) as in Fig. 4. The approximate position of the surface dryline is included for reference.
FIG. 16. As in Fig. 15, but for the 0–6-km shear vector (barbs, m s$^{-1}$) and 0–3-km SRH (contours, m$^2$ s$^{-2}$) from the SPC mesoanalyses. Barb values are as in Fig. 4.
FIG. 17. As in Fig. 15, but for 100-hPa mixed layer CAPE (contours, J kg$^{-1}$) from the SPC mesoanalyses.
wind and moisture profiles, as well as forcing mechanisms.

**a. Methods and configuration**

The model used for the idealized simulations was version 2.1.2 of the Weather Research and Forecasting (WRF) Advanced Research WRF (ARW) modeling system developed at the National Center for Atmospheric Research (NCAR; Skamarock et al. 2005). The idealized model simulations were divided into two main groups; tests of sensitivity to changes in environmental parameters, and tests of sensitivity to changes in the initiation or “trigger” mechanisms. For the majority of these simulations, the model was integrated for 6 h over a 400 km × 400 km domain with a horizontal grid spacing of 1 km. A vertical grid spacing of 500 m was used over 41 vertical levels. Convection was simulated explicitly and the Lin et al. (1983) scheme was used to parameterize the cloud and precipitation microphysics. Subgrid-scale turbulence was parameterized using a 1.5-order turbulent kinetic energy (TKE) closure. Coriolis accelerations were excluded, as simulations by Parker (2007b) demonstrated that the overall convective mode was not sensitive to them during a 6-h simulation. To further simplify the simulations, surface fluxes and radiative effects were not included in the model. The simulations used Rayleigh damping over a layer of 5 km at the model top and open lateral boundary conditions unless otherwise noted.

The homogeneous base-state environments for these simulations were based on three soundings representative of the three environments discussed in the observational case study. The 1800 UTC Lamont sounding (hereafter LMN18; Fig. 6c) represents the environment in which the supercells initially formed on 30 March 2006, and the TSF composite sounding (hereafter TSF) represents the environment where the PS line formed (Fig. 6a). The 1800 UTC Topeka sounding (hereafter TOP18) was utilized to simulate the environment in eastern Kansas where the LS line formed (Fig. 6b). The TOP18 sounding contained a weak cap at approximately 750 hPa (Fig. 6b), which was found to inhibit long-lived convection within the simulations. To remedy this, a second sounding was created wherein the cap was removed by nudging the temperature profile within the cap layer toward increasingly cooler moist adiabats until sustained convection was achieved within the model. The resultant sounding (hereafter TOP18nocap) is shown in Fig. 19.

Convection was initiated within these simulations using a variety of initial perturbations to simulate a range of isolated and linear forcings for storms (Fig. 20). The most basic trigger, used to provide a baseline control experiment, was a single thermal bubble with a horizontal diameter of 10 km and a vertical diameter of 3
km, centered at 1.5 km above ground level (AGL). The bubble was 3 K warmer than the surrounding environment at its center, with a Gaussian temperature decrease toward its outer edges. Other simulations incorporated lines of three and five of these bubbles, using a variety of different bubble spacings and several different orientations, similar to the approach of Bluestein and Weisman (2000). These configurations were designed to mimic the early stages of the observed supercells and PS line, both of which developed from initially isolated cells along the dryline. Additionally, a warm-line thermal and several variations based on an initial cold box, including a simulated outflow boundary collision, were used to emulate the linear lifting mechanism observed with the LS line (see Fig. 20). For the colliding outflow simulations, periodic $x$- and $y$-lateral boundary conditions were used to limit the computational noise produced by the initial cold pool intersecting the lateral boundary. The model domain was also extended in the $x$ direction for these simulations to minimize the impact of the periodic $x$-lateral boundary conditions on the simulated storms.

b. Environmental control simulations

To establish control runs, idealized simulations were performed using each of the initial soundings and a single warm bubble perturbation to initiate convection. The single-bubble simulations established the relation-
ship between a given environment and its predominant convective mode while at the same time providing benchmarks with which to compare further sensitivity tests.

The first experiment used the LMN18 sounding, characterized by a moderate amount of CAPE and strong wind shear. The single bubble triggered an isolated multicell storm, periodically developing new updrafts along the right flank of the storm (not shown). While some of the stronger updrafts contained maxima in the vertical vorticity, the close proximity of these initial cells led to frequent mergers that precluded any one updraft from becoming well organized and developing supercell characteristics (Figs. 21a and 21b). As the surface cold pool grew in size, new cells began developing away from the mature storms, making collisions less frequent. This allowed individual storms to become more intense and organized and by 3 h, storms began to emerge featuring supercell characteristics (Figs. 21c and 21d). The first of these (cell C1) had developed a strong updraft with a midlevel mesocyclone, characteristic of a supercell; however, this cell was limited in its intensity by continued (albeit less frequent) collisions with other storms (Figs. 21c and 21d). The second intense storm (cell C2) rapidly intensified and began moving to the right of its initial storm motion while developing a midlevel mesocyclone, as evidenced by a vorticity maximum (Figs. 21c and 21d).
FIG. 21. Evolution of convection triggered using a single warm bubble in the LMN18 environment. Simulated radar reflectivity at 3 km (dBZ, shaded) and the edge of the surface cold pool, denoted by the −1 K potential temperature perturbation (heavy contour) at (a) 60, (c) 180, and (e) 360 min into the simulation. The 6-km vertical velocity (m s⁻¹, shaded) and vorticity (contoured at an interval of 0.005 s⁻¹, with the 0 contour omitted) and the edge of the surface cold pool, denoted by the −1 K potential temperature perturbation (heavy contour) at (b) 60, (d) 180, and (f) 360 min into the simulation. Note, only a portion of the domain is shown in order to highlight the storm details.
matured into an isolated supercell, becoming the pre-
dominate storm present by the end of the simulation
(Figs. 21e and 21f). This process is very similar to the
multicell to supercell transition described by Vasiloff et
al. (1986), and may help explain the early evolution of
the supercell storms observed on 30 March 2006. The
observed storms developed as a broken line of largely
multicell structures (Fig. 8a) and did not organize into
supercells until 1–2 h after initiation (Figs. 9a and 9b).
Given the similarities in behavior between the observed
and simulated storms, these results would suggest that
the high-shear LMN18 environment effectively repre-
sents the environment that featured isolated supercells
on 30 March 2006.

The second environment represented eastern Kansas
(where the LS system was observed) and was charac-
terized by the TOP18nocap sounding. This region was
very similar to the supercell environment, except that
the 0–6-km bulk shear vector magnitude was approxi-
mately 6–8 m s$^{-1}$ weaker. The single-bubble simulation
resulted in a splitting supercell (Figs. 22a and 22b) with
isolated right- and left-moving cells. The right-moving
storm was the more intense and organized of the two,
maintaining supercell characteristics including hook-
shaped simulated radar reflectivity signatures and a
midlevel mesocyclone for the duration of the 6-h
simulation (Figs. 22c and 22f). The left-moving
storm was considerably smaller and had begun to dis-
sipate by 3 h into the simulation (Figs. 22c and 22d),
losing most of its organization by 4 h (not shown). In
short, absent linear forcing, the eastern Kansas envi-
rone appeared to have adequate shear to support
supercells.

The final environment is that of the PS line that
formed in west-central Kansas, characterized by the
TSF sounding. This environment featured dry air aloft
and southerly midlevel winds largely parallel to the sur-
face dryline. The simulated convection began as an iso-
lated multicell (Fig. 23a), evolving upscale first into an
MCS (Fig. 23b), and eventually into a TS linear MCS
that reoriented itself from north–south to northwest–
southeast (Figs. 23c and 23d). This reorientation was
the result of convective development being favored on
the downshear edge of the cold pool as suggested by
Rotunno et al. (1988). While this rapid evolution to-
ward a TS structure was not observed in the actual case,
it should be noted that similar reorientation was seen in
the PS simulations of Parker (2007a). In the observed
case, the dryline likely prevented this reorientation
from happening, as the PS storm remained just east of
and oriented parallel to it throughout its lifespan. This
simulation was too simple to replicate the exact
structure that was observed (PS); however, it did gen-
erate long-lived linear convection with a strong cold
pool ($\theta' = -10$ K), as well as subsequent evolution
toward the TS precipitation structure. This would sug-
gest that the TSF environment favors linear modes,
such as the PS line that was observed.

c. Initial perturbation sensitivities

Following the single-bubble control experiments,
simulations were run within each environment using
the variety of initial perturbations outlined in section 3a
(Fig. 20). In general, these simulations revealed surpris-
ingly little sensitivity to the initiation mechanism across
all three of the environments. While there were short-
term changes to the areal coverage of the early storms,
by 3 h into the simulations these effects had largely
dissipated. By 6 h, the modal characteristics of the
storms within these simulations were very similar to
what was seen in the control simulations (not shown).

The notable exceptions to these findings were simul-
ations run within the TOP18nocap environment using
the cold box initiation mechanism and within the
TOP18 environment using the colliding outflow bound-
ary. The TOP18nocap simulation with the cold box
generated a linear MCS with LS characteristics through
approximately 2–3 h (Fig. 24a), after which it evolved
toward a TS structure (Fig. 24b). Similarly, the colliding
outflow boundary simulation generated a leading strati-
form MCS (Fig. 25), as was seen in the observed case.
No isolated structures were present in either of these
simulations, which was a dramatic departure from the
control simulation. Additionally, the outflow collision
was the only simulation that was able to create sus-
tained convection within the TOP18 environment, by
generating sufficient vertical motion (Fig. 26a) to over-
come the CIN present in the environment (Fig. 6b).
Simulations run with the aforementioned warm thermal
perturbations failed to develop long-lived convection,
as did simulations run using just the eastern and west-
ern halves of the outflow collision simulation (Figs. 26b
and 26c).

These findings would suggest that the outflow bound-
ary collision played a key role in the development of
the LS line. First, it provided sufficient vertical motion
to overcome the cap present within the TOP18 envi-
rone, making sustained convective storms possible.
Second, while the local (i.e., TOP18nocap) environ-
ment appears to favor isolated supercells in the control
simulations (Fig. 22), the cold box and colliding outflow
boundary experiments suggest that a strong linear forc-
ing mechanism can overcome this environmental pro-
clivity and generate a linear mode. This would suggest
that the development of the LS line on 30 March 2006
was as much the result of the linear forcing mechanism as the background environment.

A more general finding to emerge from these simulations is that the role of the initiation mechanism appears to be strongly governed by the background environment. While a sensitivity to the initial forcing was evident with the TOPI18nocap environment, it was not present within the more selective environments. Within the LMN18 environment (which contained wind shear values well within the supercell regime) simulations run using the same initial cold box still resulted in the isolated supercell structure seen in the control simulation (Fig. 27). Thus, the role of the initiation mechanism in determining mode is likely governed by how strongly an environment favors a given mode. It should be noted that within these simulations, no attempts were made to control whether a storm remained near its initial forcing or to maintain said forcing during the storm’s life-

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**Fig. 22.** As in Fig. 21, but for TOPI18nocap environment. Note, (c) and (d) show a larger area in order to include both the left- and right-moving storms.
In situations where storms are initiated and continue to reside along strong linear forcing, such as a dryline or front, the linear feature can indeed play an important role in how the organizational mode evolves over time (Jewett and Wilhelmson 2006). Therefore, our finding is likely more applicable in cases where storms are initiated by a feature and then move away from it as they mature.

**d. Environmental sensitivities**

To further examine the roles of the three different environments in generating three different modes of convection on 30 March 2006, a battery of simulations was run to isolate the variations in the thermodynamic and vertical wind shear profiles among the environments. The wind profile from each sounding was paired with the thermodynamic environments from each of the other soundings, resulting in the matrix of combinations reported in Table 1. Although even more dramatic variations in the convective environment could easily be envisioned, this approach helped us to quantify the relative importance of the observed differences among the PS, LS, and supercell environments on 30 March 2006. For this series of simulations, the 200-km warm line thermal was used to initiate convection, because it mimicked the linear forcing seen in reality.

**Fig. 23. Evolution of convection triggered using a single warm bubble in the TSF environment.** Simulated radar reflectivity at 3 km (dBZ, shaded) and the edge of the surface cold pool, denoted by the $-1$ K potential temperature perturbation (heavy contour) at (a) 90, (b) 180, (c) 270, and (d) 360 min into the simulation. Note, only a portion of the domain is shown in order to highlight the storm details.
along the dryline and outflow collision, while also readily allowing isolated structures to evolve (as seen in the experiments above).

The resultant modes observed in these various simulations are summarized in Table 1. Generally, aside from the simulations using the TSF thermodynamic profile, the ultimate mode was an isolated supercell (similar to those seen in the LMN18 and TOP18nocap control simulations; Figs. 21 and 22). This further illustrates that isolated supercells are the environmentally favored mode for both the LMN18 and TOP18 environments. Additionally, absent the dry air aloft, the

![Fig. 24. As in Fig. 23, but showing the 6-km simulated radar reflectivities (dBZ) at (a) 120 and (b) 240 min for the TOP18nocap environment initiated with a 50 km × 100 km cold box. Simulated radar reflectivity was plotted at 6 km (rather than 3 km) in order to accentuate the positions of the stratiform precipitation regions.](image)

![Fig. 25. East–west vertical cross section of simulated radar reflectivity (dBZ) and wind vectors consisting of the u and w components of the wind (m s⁻¹) at 45 min for the TOP18 colliding outflow boundary simulation.](image)
TSF wind profile favors isolated supercells as well, suggesting that the linear mode is more strongly tied to the thermodynamic environment. Simulations run using the TSF thermodynamic environment overwhelmingly favored the TS mode (similar to that seen in the TSF control simulations; Fig. 23). The importance of the dry air aloft in the TSF environment became evident: when it was present, a squall line was simulated independent of the wind profile, while without it, the TSF wind profile favored an isolated mode. Additionally, these results underscore the importance of the linear forcing in the development of the LS line, as neither the wind, nor thermodynamic profiles within the TOP18 environment, supported linear modes in the absence of such forcing.

4. Conclusions

Forecasting the convective mode has traditionally been understood in terms of the environment in which storms are expected to occur. The findings of this study largely support this approach but also make it clear that large-scale evaluation of basic indices such as CAPE and bulk wind shear alone are far from deterministic. Rather it is the mesoscale variations in these parameters, sometimes in concert with a particular forcing...
mechanism, that determine the observed convective mode (Fig. 28).

This was particularly evident along the dryline in this case, as environmental variations led to the development of two distinct modes from the same initiating mechanism (Fig. 28). While copious instability and strong shear were present all along this boundary, locally intense shear (25–28 m s\(^{-1}\)) that was oriented at approximately 45° to the boundary, coupled with locally strong SRH, provided an enhanced opportunity for supercell development in western Oklahoma. At the same time, slightly weaker (20–22 m s\(^{-1}\)) shear oriented parallel to the dryline, coupled with dry air aloft, favored a linear mode farther north in Kansas where the PS line formed. Additionally, a variation in the direction of the midlevel winds was likely significant, with across-boundary flow allowing the supercells to move off the dryline and remain isolated, and along-boundary flow keeping the PS line anchored just ahead of the linear forcing of the dryline throughout its lifetime. It was likely the close proximity to the dryline that prevented the downshear reorientation seen in the model simulations, helping to maintain the PS mode for several hours before its ultimate transition to TS.

The formation of the LS line was governed more significantly by the initiation mechanism, as it developed largely in response to the strong linear forcing provided by a collision between two outflow boundaries in eastern Kansas (Fig. 28). Its environment was characterized by comparatively weaker shear values falling between the multicell and supercell regimes. This environment was less selective of the convective mode (compared to the supercell and PS environments), and thus storm organization was governed much more strongly by the initiation mechanism. In idealized simulations using this environment, isolated forcings led to supercells, whereas a strong linear forcing led to a squall line. It is notable that, within the higher-shear LMN18 environment, even a strong linear forcing could not overcome the environmental proclivity for isolated supercells. Thus, it was the combination of a strong linear forcing within the accommodating moderate shear environment that resulted in the LS development.

The results discussed in this work suggest that environmental factors are of primary importance in differentiating between convective modes. The storm initiation mechanism, in cases where the forcing is transient, plays a secondary role and is only significant to mode determination within environments that do not strongly favor a particular organization. While this is in line with past work on the subject, the emphasis here is on localized (meso–beta scale) variations in parameters such as vertical shear and moisture profiles. The challenge,

<table>
<thead>
<tr>
<th>Thermodynamic profile</th>
<th>Wind profile</th>
<th>Simulated mode (6 h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMN18</td>
<td>LMN18</td>
<td>Isolated supercell</td>
</tr>
<tr>
<td>TOP18nocap</td>
<td>TOP18</td>
<td>Isolated supercell</td>
</tr>
<tr>
<td>TSF</td>
<td>TSF</td>
<td>TS squall line</td>
</tr>
<tr>
<td>LMN18</td>
<td>TOP18</td>
<td>Isolated supercell</td>
</tr>
<tr>
<td>LMN18</td>
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<td>Isolated supercell</td>
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<tr>
<td>TOP18nocap</td>
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<td>Isolated supercell</td>
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<td>TSF</td>
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<tr>
<td>TSF</td>
<td>TOP18</td>
<td>TS squall line</td>
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</tbody>
</table>

Fig. 27. As in Figs. 21e and 21f, except initiated with a 50 km × 100 km cold box.
however, is that these fields are more commonly observed and analyzed on the meso-alpha to synoptic scales. Better observations on smaller temporal and spatial scales are needed in order to resolve these variations in real time and, thus, make them relevant to the forecaster. This would no doubt enhance forecasts of convective mode and provide better anticipation of associated severe weather threats.

Through the course of this study several possible avenues of future work have emerged. First and foremost, further investigation of the evolution of convective modes would be useful, especially the effect that movement into a different environment has on storm mode. Also, it is clear that idealized simulations have limitations in such complex scenarios. For example, the continued reorientation of MCSs to be perpendicular to the vertical shear (as seen in the TSF simulations) precluded an accurate simulation of the PS structure. Determining the features in nature that prevent this from happening, and finding a means to simulate them, would no doubt be useful to both this and other research in the field. Finally, this study suggests that the storm mode is largely dependent on background environmental features, both during a storm’s initiation as well as during its evolution. However, it is likely that in cases where multiple storms are evolving in close proximity, they may be altering their nearby environments and in doing so altering the environments of the surrounding storms as well. Such effects could have important implications for storm evolution and merit further investigation.

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FIG. 28. Schematic diagram that summarizes the three regions for storm initiation on 30 Mar 2006. Hatched areas represent the areas of the local environments associated with each mode, large black arrows represent 0–6-km shear vectors, and large gray arrows 500-hPa wind vectors. The surface dryline is denoted by a scalloped line, and the colliding outflow boundaries by lines with pointed pips.
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