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Evolution and Maintenance of the 22–23 June 2003 Nocturnal Convection during BAMEX

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ABSTRACT

On 22–23 June 2003 a broad region of convection, comprising a squall line and discrete supercells, evolved throughout the evening and nighttime hours. These storms were studied by analyzing both observations and idealized numerical simulations. The squall line originated from a group of supercells that were initiated in a north–south line along a preexisting outflow boundary in eastern Nebraska. These supercells anchored to the boundary, facilitating cell mergers. The cell mergers and subsequent enhanced rainfall increased the depth and strength of the surface cold pool, which became the forcing mechanism for reorientation into an east–west, southward-propagating squall line. While this was occurring, isolated supercells developed along the dryline in north-central Kansas. These supercells moved northeastward throughout the night. These two modes of convection developed and evolved in a similar nocturnal environment, suggesting that there were two distinct forcing mechanisms responsible for their maintenance. The nocturnal boundary layer was stable; however, CAPE existed and convection would have been able to remain surface based so long as near-surface air was being lifted to its level of free convection (LFC). In this study, both cold pool dynamics and supercell dynamics appear to have played an important roll in lifting low-level air to its LFC throughout the night.

1. Introduction

In the central Great Plains, a nocturnal maximum in organized convection exists (e.g., Carbone et al. 2002). Forecasting nocturnal convection is difficult because the mechanisms that sustain these convective systems are poorly understood (McNulty 1995). Convective storms, including supercells and mesoscale convective systems, are often referred to as being either elevated (e.g., Colman 1990a,b; Rochette and Moore 1996; Fritsch and Forbes 2001; Moore et al. 2003; Horgan et al. 2007; Corfidi et al. 2008) or, alternatively, surface based, depending upon the height of origin of the air parcels that are sustaining them. Elevated convective storms, here defined as active storms not ingesting air from the near-surface layer (i.e., below 500 m AGL), are less likely to produce severe surface winds and tornadoes (as reviewed by Horgan et al. 2007). However, while convection is often assumed to be exclusively in one of these two categories, mature thunderstorm systems may often be a hybrid of the two (e.g., Corfidi et al. 2008; Trier et al. 2011), ingesting both surface-based air, as well as unstable air from above the boundary layer. It is important for operational forecasters to be mindful of the possibility for nocturnal surface-based thunderstorms because of their potential for tornadoes and severe winds. Therefore, it is a worthwhile forecasting challenge to determine whether storms are likely to be elevated, or at least partially surface based.

During the nighttime hours, the stabilization of the planetary boundary layer (PBL) restricts the formation of convection and its associated cold pools. Nocturnal convection, especially that associated with the low-level jet [e.g., the "type 1" systems of Fritsch and Forbes (2001)], is therefore often thought to be elevated. However, the idealized simulations of Parker (2008) and Nowotarski et al. (2011) show that convective systems and supercells may remain partly surface based even when the low levels are quite stable. In order for operational forecasts to improve, our knowledge of the physical processes governing nocturnal convection must be advanced. Toward that aim, it is worthwhile to try to

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understand whether particular nocturnal environments are conducive to elevated or surface-based convective storms and what mechanisms are responsible for lifting air parcels to their levels of free convection (LFC) in each case.

This research is based on a case study of nocturnal storms that occurred over eastern Nebraska and north-central Kansas on 22–23 June 2003 and that were sampled by the Bow Echo and Mesoscale Convective Vortex (MCV) Experiment (BAMEX; Davis et al. 2004). In the case presented here, isolated thunderstorms began as surface-based storms during the late evening hours, and then the atmospheric boundary layer slowly cooled nocturnally, bringing into question whether the storms remained surface based, or became elevated during the night. The evolution from isolated supercells during the evening to a complex nocturnal system containing both a slowly moving squall line and isolated northeast-moving storms makes this event particularly interesting. The characteristic dynamics of both squall lines and supercells may be important in cases of nocturnal convection, and we review them in turn.

Nocturnal stable layers support gravity waves, and air with convective available potential energy (CAPE) above the stable layer may be lifted by such waves in the absence of a front or low-level jet, leading to linear convective structures (Schmidt and Cotton 1989; Carbone et al. 1990; Parker 2008; Schumacher and Johnson 2008; French and Parker 2010). However, Parker (2008) showed that cold pool lifting can overcome a substantial amount of low-level cooling, enabling a nocturnal squall line to remain surface based. Along these lines, the idealized simulations of Bryan and Weisman (2006) and Parker (2008) also showed that severe surface winds can be associated with nocturnal-like convection when atmospheric boundary layer air is being ingested due to lifting by a deep surface-based cold pool. Indeed, Kuchera and Parker (2006) found that, once storms had developed, convective inhibition (CIN) was not a particularly useful parameter in determining whether severe convective winds would continue; the principal requirement was that the low-level air continued to possess CAPE. Taken altogether, these studies support the concept that squall lines may remain cold pool driven and surface based during the nighttime hours. The squall line in this study continued to move in the direction of its surface-based cold pool even after the boundary layer was stabilized, suggesting that it may be one such example.

It has also long been known that a dynamically induced perturbation vertical pressure gradient force in supercells can lift environmental air even when its buoyancy is small or negative (Rotunno and Klemp 1982, 1985; Weisman and Klemp 1984; Klemp 1987; Weisman and Rotunno 2000). Such a mechanism also suggests itself as a means of sustaining surface-based convection in the stable nocturnal boundary layer. Nowotarski et al. (2011) performed a matrix of supercell simulations in which a low-level inversion was present, and found updrafts that continued to ingest air parcels from the stable layer. A group of supercells in this study persisted through the nighttime hours and produced tornadoes well after local sunset, implying that they may have been surface based (e.g., as described by Davies-Jones et al. 2001).

The following sections analyze the evolution of the nocturnal storms on 22–23 June 2003. Section 2 presents the observational analysis of the primary supercells and squall line. The analysis of the observations leads to hypotheses, which are then evaluated using numerical experiments, as reported in section 3. Section 4 closes this publication by summarizing the results of the study.

2. Observational analysis

a. Methods

BAMEX was an observational field program conducted between 20 May and 6 July 2003 in the central United States. (Davis et al. 2004). Several key dropsondes provided a high-resolution depiction of the near-storm environment on 22–23 June (Fig. 1). Additionally, operational NWS soundings from Omaha, Nebraska (OAX); North Platte, Nebraska (LBF); and Topeka,
Kansas (TOP), were also used to depict the vertical profile of the prestorm environment near the evening’s storms (Fig. 1). Although two airborne radars were deployed during BAMEX, the main goal of the experiment was to study bow echoes and MCVs; therefore, the aircraft returned to base around 0700 UTC, leaving a void in the airborne radar data for the remainder of the storms’ nocturnal life cycles. Even when the aircraft were on site, the airborne radars did not depict the lowest 1 km of the atmosphere well, so their data could not be used to determine if convection was elevated or surface based. For the sake of temporal continuity, and the need for radar data close to the ground, the Weather Surveillance Radar-1988 Doppler (WSR-88D) Next Generation Weather Radar (NEXRAD) level II data were utilized to depict the storms’ initiations and evolutions, including the radars at OAX; TOP; Hastings, Nebraska (UEX); and Dodge City, Kansas (DDC) (Fig. 1).

The above observations were supplemented with ground-based Automated Surface Observing Systems (ASOS) measurements and North American Regional Reanalysis (NARR) data. The ASOS data were analyzed by hand for each hour between 1800 UTC 22 June and 1200 UTC 23 June 2003 and the NARR upper-air data at mandatory levels were used to depict the synoptic environment of the event.

b. Preconvective environment

The synoptic environment for the 22–23 June 2003 episode (Fig. 2) was characterized by a broad mid- and upper-level trough over the western half of the United States, with a closed low just off the coast of the northeastern United States (Fig. 2a). The central Great Plains were under a diffuent upper-flow regime along the very southern edge of a southwesterly 250-hPa jet streak (not shown). An 850-hPa jet was present over central Kansas, extending into south-central Nebraska during the overnight hours prior to the 22 June episode. The strong nocturnal low-level jet and continuing southerly daytime 850-hPa winds advected moisture northward into eastern Nebraska leading up to the event (Fig. 2b). The nocturnal low-level jet was also present throughout the morning hours of the event on 23 June 2003, and it continued to provide a source of low-level moisture for the storms. At the surface throughout the event, a high pressure system dominated the Midwest (not shown) while a stationary front was draped across the central plains (Fig. 3).

Scattered thunderstorms occurred over the central plains on the evening of 21 June 2003 (roughly 24 h before our case study) and moved into eastern Nebraska by the early morning hours of 22 June 2003; they can be seen as remnant cloudiness over northern Missouri by 2200 UTC in Fig. 3. The thunderstorms from the morning of 22 June produced a stable and persistent airmass in the wake of an outflow boundary over the majority of eastern Nebraska and surrounding states (Fig. 3). The outflow boundary slowly moved westward into central Nebraska throughout the day. To the south and west of the outflow boundary, solar heating warmed and destabilized the atmosphere. This warm sector had high mixed layer convective available potential energy (ML CAPE ≈ 4800 J kg⁻¹; Fig. 4a), and very little mixed layer convective inhibition (ML CIN ≈ −19 J kg⁻¹; Fig. 4a). The vertical wind shear profile was supportive of supercells due to the deep layer of shear and high storm relative helicity (381 m² s⁻²). However, within the preexisting outflow, mainly over eastern Nebraska (e.g., at OAX), the surface temperatures were approximately 5 K lower, such that the environment (Fig. 4b) had less ML CAPE (4042 J kg⁻¹) and more ML CIN (−123 J kg⁻¹) than the prevailing environment. The western edge of the outflow boundary was roughly aligned from north to south in central Nebraska (Fig. 5a), while the southern edge was aligned from west to east over extreme northeastern Kansas (Fig. 3). This orientation of the outflow boundary was key in the eventual evolution of the observed squall line.

Finally, a dryline extended from north-central Nebraska, near the outflow boundary, through western Kansas and south through the Oklahoma panhandle and into the Texas Panhandle (Fig. 3). This provided a second focus for storm development in addition to the outflow boundary. With the presence of lifting mechanisms, instability, and strong vertical wind shear, the warm moist sector between the dryline and outflow boundary was primed for the development of severe thunderstorms over eastern Nebraska and northeastern Kansas.

c. Radar observations

Isolated storms were initiated on the western edge of the north–south-oriented outflow boundary in south-central Nebraska around 2200 UTC 22 June 2003. Some of these storms quickly matured into supercells by 0000 UTC. The Aurora, Nebraska, supercell (storm A; Fig. 5) began near Hastings and was the southernmost member of a line of isolated storms that eventually merged together. This powerful supercell produced record-breaking hailstones in Aurora (Knight and Knight 2005) and two tornadoes rated as category 0 on the Fujita scale (F0; NCDC 2008). The Deshler, Nebraska, supercell (storm D; Figs. 5a,b) developed and became quasi stationary along the preexisting outflow boundary. The Deshler storm remained quasi stationary for roughly 3 h, while other storms developed to its southwest and merged with it (not shown).
Between 2200 UTC 22 June and 0200 UTC 23 June 2003, at least six individual storms merged with the Deshler supercell. These mergers impacted the Deshler supercell’s evolution and subsequent characteristics. Following the storm mergers, the Deshler supercell spawned four separate weak tornadoes [F0–F2 intensity; NCDC (2008)] near the town of Deshler, between 2230 and 2320 UTC. After all of the storm mergers, the Deshler storm was no longer rotating and was dominated by low-level outflow (Figs. 5b,c). Apparently, this ultimately cut off the updraft of the Deshler storm and led to its demise. Meanwhile, a new dominant supercell (the Superior supercell, storm S; Figs. 5b–e) developed near Superior, Nebraska, to the south of the dissipating Deshler supercell. The Superior supercell was also associated with weak tornadoes.

Fig. 2. Synoptic environment analysis depicted from NARR data at 0000 UTC 23 Jun 2003. Constant pressure plots at (a) 500-hPa height (solid contours; interval is 60 m), isotherms (°C, dashed contours; interval is 5°C), and wind barbs (kt; where 1 kt = 0.514 m s⁻¹) and (b) 850-hPa height (solid contours; interval is 30 m), isotherms (°C, dashed contours; interval is 5°C), mixing ratio (shaded with an interval of 2 g kg⁻¹), and winds barbs (kt).
and large amounts of accumulated rainfall throughout the event, as well as the strongest mesocyclone ever measured (Wakimoto et al. 2004). The Superior supercell was quasi stationary throughout its lifetime, similar to the Deshler supercell, anchoring to the preexisting outflow boundary and continuing to ingest the high-$\Theta_v$ air from south of the boundary.

Bluestein and Weisman (2000) noted that, under a number of conditions, supercells with deviant motion often approach and merge with one another. Such a merger may either enhance or diminish the dominant cell. A cell merger in the current study is said to occur when two reflectivity cores approach and join one another. Merging of cells often leads to enhanced precipitation production (Changnon 1976; Lemon 1976; Simpson et al. 1980; Tao and Simpson 1984; Westcott 1994), possibly due to reduced entrainment of dry air and increased precipitation efficiency from seeding and accretion that are enhanced by the large volume of hydrometers among the merged cells. In addition to the enhanced precipitation production, it has also been suggested in the literature that cell mergers can be precursors to tornadogenesis (Lemon 1976; Finley et al. 2001; Lee et al. 2006). In observational studies by Lemon (1976) and Finley et al. (2001), and numerical studies by Kulie and Lin (1998), updraft strength and midlevel rotation increased after a cell merger. Following the mergers of the isolated storms with the Deshler supercell, and then with the subsequent Superior supercell, the latter storm was responsible for six weak tornadoes in north-central Kansas. More importantly, the mergers, especially with the Deshler supercell, appeared to enhance the precipitation associated with the quasi-stationary supercells, with measured rainfall amounts of approximately 12 in. near Deshler (NCDC 2008). It is hypothesized that this enhanced precipitation and subsequent evaporative cooling increased the strength of the cold pool. By 0330 UTC the mesocyclone in the Superior supercell had dissipated, with only a strong outflow and elongated reflectivity core remaining (Figs. 5d,e). The outflow appeared to be the dominant forcing for new convection that developed, preferentially along the south side of the previous supercells. The development of the cold pool ushered in a new convective regime, with storms evolving into an east–west, southward-propagating squall line between 0330 and 0800 UTC (Fig. 6).
Meanwhile, in the early evening hours (~0130 UTC), additional isolated storms were also being initiated along the dryline in north-central Kansas (oval in Fig. 5b). These storms moved toward the northeast due to the southwesterly mean cloud layer winds (e.g., Figs. 2a, 4a), with some of them becoming supercells. One of these supercells (shown along the western end of Fig. 6a) produced three weak F0 tornadoes in Phillips and Smith

Fig. 4. Skew T–logp plots and hodographs at 0000 UTC 23 Jun 2003 from (a) KTOP and (b) KOAX.
 Counties in Kansas between 0600 and 0700 UTC. New storms continued to develop along the western flank of the southward-moving squall line (Fig. 6a), seemingly connecting the two different modes of convection for a time (Fig. 6b). The supercells and squall line coexisted in close proximity to one another for a relatively long period (0400–0800 UTC), all the while retaining their different motion vectors. Additional new storms (Fig. 6c) continued to form to the west and move toward the northeast well into the early morning hours.

**Fig. 5.** UEX base-scan reflectivities and velocities depicting early evolution of the case. (a) Radar reflectivity at 0033 UTC 23 Jun 2003, (b) radar reflectivity and (c) radial velocity inset at 0208 UTC 23 Jun 2003, and (d) radar reflectivity and (e) radial velocity inset at 0332 UTC 23 Jun 2003. Storms of interest are labeled for reference in the text.
d. Thermodynamic analysis

During the nighttime and early morning hours the environment experienced nocturnal radiative cooling, which stabilized the nocturnal planetary boundary layer (PBL) and would tend to suppress surface-based convection. At Manhattan, Kansas (MHK), a radiative nocturnal temperature drop occurred overnight with approximately a 4-K surface temperature decrease seen between 0000 and 0800 UTC based on hourly temperature data. Even so, the cold pool present over southeastern Nebraska and northeastern Kansas remained approximately 4–5 K cooler than the surrounding environment. Between 0500 and 0600 UTC the Concordia (CNK), Kansas, ASOS (for location see Fig. 1) recorded a temperature drop of 7 K and a wind shift at the time of the outflow boundary’s passage (Fig. 6a). In addition, dropsondes from near the squall line suggested the continuing presence of the cold pool. Dropsonde 11 was released at 0546 UTC (Fig. 7a), behind the squall line, while dropsonde 17 was released at 0634 UTC (Fig. 7b), ahead of the leading edge of the squall line. A comparison of the two soundings reveals a postline cold pool that was approximately 3.6°C colder than the environment and approximately 1.7 km deep (Bryan et al. 2005). However, because dropsonde 11 was well behind the leading edge of the cold pool, this is likely neither the cold pool’s maximum temperature difference nor depth (e.g., the 7-K surface temperature drop observed at CNK).

Altogether, these observations support the hypothesis that there was a surface cold pool slowly moving southward, and that the decrease in temperature and change in wind direction were not caused by larger-scale forcing (at Manhattan, approximately 104 km southeast of CNK, neither the wind shift nor abrupt temperature change was observed). The presence of this cold pool could potentially have provided enough lifting for the nocturnal
convective system to continue to ingest boundary layer air and remain surface based (e.g., Parker 2008). The pre–cold pool environment (e.g., dropsonde 17) had large surface-based CAPE (2524 J kg\(^{-1}\)), but also significant surface-based CIN (\(-186\) J kg\(^{-1}\)). To realize the surface-based CAPE, deep lifting would be needed. Doppler radar velocities show that the northerly outflow winds were approximately 2–2.5 km deep (Fig. 8), comparable to the height of the surface-based LFC in front of the squall line (calculated from dropsonde 17). It therefore appears that the observed cold pool was capable of sustaining surface-based convection. It is difficult to definitively prove that the system was not elevated, but Parker (2008) showed that a symptom of elevated squall lines is “underflow,” in which surface air does not acquire its LFC and simply passes under the convective region. This does not appear to be the case on 23 June: no underflow regime was evident in the surface observations (CNK experienced a wind shift) nor in the radar velocities (Fig. 8). Altogether, the observational evidence supports the hypothesis that the squall line continued to ingest surface-based air and remain cold pool driven throughout the nocturnal hours. The slow southward propagation of the cold pool explains the squall line’s southward storm motion in an environment with prevailing southerly flow.
Meanwhile, dropsonde 15 was released at 0618 UTC (Fig. 7c) over north-central Kansas near the northeastward-moving group of storms. The environment there also had large surface-based CAPE (2960 J kg$^{-1}$) and large surface-based CIN (−219 J kg$^{-1}$). Such CIN would likely suppress surface-based convection without a strong lifting mechanism. However, the continued production of tornadoes beyond 0600 UTC suggests that the northeastward-moving storms were indeed at least partially surface based, as high-vorticity air from the surface must be stretched in the storm updraft for a tornado to occur (e.g., Davies-Jones et al. 2001). Large-scale warm advection and ascent provided a broad environment that was favorable for convection, although the isolated nature of the supercells implies that they were individually triggered and sustained on a much smaller scale. One hypothesis is that the near-surface air was being lifted dynamically by the vertical perturbation pressure gradient force. However, not all of the northeastward-moving storms were supercells; it is possible that the supercells were surface based, whereas the nonsupercells were feeding on the moist, unstable air that was located above the nocturnal boundary layer (e.g., at 800 hPa in Fig. 7c). It is also possible that the storms were initially surface based in north-central Kansas, but gradually became elevated as the evening progressed (presumably after the tornadoes occurred).

e. Observational summary

Two different regions of convection were in close proximity to one another during the early morning hours of 23 June 2003. The two regions had different organizational structures (supercells versus a squall line) and motion vectors, suggesting that each mode was being forced differently. Observational evidence leads to the working hypothesis that the nocturnal squall line was cold pool driven and surface based. It is unclear whether the
nocturnal northeastward-moving storms were surface based or elevated, nor how they were maintained; our working hypothesis is that the supercells remained surface based because their dynamic lifting was able to overcome the environmental CIN. To test these working hypotheses, idealized numerical simulations were undertaken.

3. Idealized simulations

Idealized simulations were undertaken in order to simulate and isolate the processes that were important for the evolution of the observed storms. We undertook a series of increasingly complex sensitivity experiments designed to mimic the observed features of the 22–23 June episode.

a. Methods

Cloud Model version 1 (CM1), release 11, was used to conduct the idealized model simulations. The model’s dynamical framework was described by Bryan and Fritsch (2002). All of the idealized simulations were performed using the same basic model configuration. Cloud microphysics were parameterized with the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) version of the Lin et al. (1983) scheme, in which the graupel category was tuned for hail. In the interest of simple, highly controlled, pedagogical experiments, neither surface fluxes nor Coriolis accelerations were included. The model domain size varied among the different experiments, but the horizontal grid spacing of 1 km was kept constant in both the x and y directions. The domain height was 20 km for all simulations, with an average vertical grid spacing of 350 m, stretched from 200 m at the surface to 500 m aloft. All of the lateral boundaries were open–radiative to allow gravity waves to propagate off of the domain. The top and bottom boundaries were free-slip rigid plates, with a Rayleigh wave–absorbing layer in the model stratosphere. To reduce small-scale numerical noise, sixth-order monotonic horizontal and vertical diffusion were also used.

The homogeneous initial conditions used for these simulations were given by a point sounding (Fig. 9a) from south-central Nebraska in a quasi-operational run of the Weather Research and Forecasting (WRF) model (not shown), valid at 0130 UTC 23 June 2003 (just over 7 h into the model run). This was around the time that the supercells in central Kansas began to develop (see the dashed oval in Fig. 5b). The nearby observational soundings (0000 UTC soundings from OAX and TOP; BAMEX dropsondes from 0500 to 0700 UTC) were not as amenable to the simple, homogeneous modeling experiments because it was difficult to initiate long-lived convection in the presence of temperature inversions (in the case of the 0000 UTC soundings) or in a stable boundary layer (in the case of the dropsondes). Through experimentation, the model gridpoint sounding was deemed to be sufficiently representative of the early evening environment in order for our sensitivity tests to replicate the observed convective behavior. The point sounding had a wind profile that supported supercells, as well as large CAPE (4348 J kg$^{-1}$) and negligible CIN ($-11$ J kg$^{-1}$), which allowed long-lived convection. Convection was initiated in the idealized domain using various warm bubble and cold pool configurations (Table 1); these triggers, and other specific run-by-run details of the simulations, are summarized in turn below.

b. Simulations with simple forcing

To better understand the environment and its role in organizing the storms on 22–23 June, simple thermal forcings were first used to initiate convection in the idealized simulations.

1) WARM BUBBLE

In the initial simulation, convection was initiated using a 3-K Gaussian warm bubble (Table 1, row 1). Within 30 min, the initial perturbation generated a supercell that split into nearly symmetrical cyclonic (right mover) and anticyclonic (left mover) storms (Fig. 10a). The precipitation from these storms created a cold pool at the surface that strengthened and spread outward for the remainder of the simulation (Fig. 10b). By $t = 3$ h, the ongoing convective storms were primarily located on the downslope (eastern) side of the surface cold pool, a configuration that is consistent with cold pool–driven squall lines (e.g., Rotunno et al. 1988). An isolated right-moving supercell, as identified in Fig. 10b inside the dashed circle, remained on the southern edge of the squall line, much as was simulated by Bluestein and Weisman (2000). There were individual cells within the squall line that had rotation and continued to split, but they remained embedded within the squall line [like those analyzed by Bluestein and Weisman (2000)]. Both the observed and simulated supercells split and moved toward the northeast. In comparison to the observed case where the left movers quickly dissipated or collided with other storms, the simulated left movers were longer lived. These left movers were longer lived in part due to the homogeneous environment, and in part because the observed environment had a more strongly clockwise-turning hodograph (Fig. 4a) than under the idealized initial conditions (Fig. 9a). There were qualitative similarities between the observed Deshler and Superior supercells and the supercells in the simulation, and much as in the simulation, a squall line did indeed develop during...
the observed event. However, its orientation was different, suggesting processes that are more complex than what this homogeneous environment and single warm bubble could capture. Even so, as a first attempt, the simple model simulation produced credible convective modes and storm motions. This helps to highlight the primary role of the preconvective environment in the subsequent evolution.
c. Simulations with combined forcing

A fundamental feature of the tests in section 3b was the preferred development of new storms on the downshear sides of cold pools in the model. Although the results of the preceding simple tests were reminiscent of the kinds of storms observed during the 22–23 June event, the observational radar analysis suggested that there were more sophisticated cell interactions at work. Because the goal of the simulations was to study convective evolution similar to what was observed, more complex initial perturbations were created to mimic the observed patterns and locations of convective development.

1) INITIATION NEAR AN OUTFLOW BOUNDARY

To simulate the development of supercells near a pre-existing outflow boundary, four warm bubbles (+3 K) were placed tangent to the western edge of a −2-K, 300-km-radius cold pool that was 1.5 km deep (Fig. 9b, excluding bubble E) within a 400 km × 600 km domain. The four warm bubbles were spaced with their centers 50 km apart, mimicking the positions of the supercells that were initiated along the preexisting outflow boundary during the observed convective event (see section 2; Fig. 3). Only the southwestern quarter of the cold pool was simulated, which saved on computations and also removed the possibility of convection forming on the cold pool’s downshear (eastern) side.

Within the first hour of the boundary simulation each warm bubble matured into a splitting supercell (Fig. 12a), just as in the isolated bubble experiment. However, their subsequent patterns of evolution were different. The motion of the northern three storms was generally toward the northeast whereas the southernmost became “anchored” to the outflow boundary and moved along it toward the southeast (Fig. 12a). The northeastward motion of storms of the three northernmost storms carried them over the cold pool, where the low-level stability was greater, reducing the storms’ intensities (Fig. 12a). One of the storms completely dissipated by the end of the simulation, while the remnants of the two northernmost storms were able to survive, evolving into a weak northeastward-moving squall line.

In contrast, by remaining along the outflow boundary and moving southeastward, the southernmost storm (Fig. 12b) was able to continue to ingest higher-Θ_e surface air, as well as enhanced storm relative helicity attributable to the baroclinic generation of horizontal vorticity along

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1 Notably, this was weaker and shallower than the observed outflow pool. However, in tests with colder, deeper cold pools, the motion of the outflow boundary was too rapid, and quickly disrupted the isolated storms. We speculate that the observed outflow was slowed because it had acquired some degree of geostrophic balance, having persisted for a period of roughly 12 h. Rather than trying to include this effect in our idealized model, we compromised by making the initial cold pool shallower and weaker.
the cold pool’s edge (e.g., Markowski et al. 1998). The high-$\Theta_v$ air explains the storm’s maintenance, while the lifting of high-helicity air into the updraft helps to explain its enhanced rotation and deviant motion. New small isolated storms continued to develop along this storms’ newly created cold pool, eventually creating a squall line reminiscent of that in central Nebraska on 22–23 June (Fig. 6b). Simulated reflectivity animations reveal that individual cells moved northeastward along the squall line as the squall line moved southward, much as in the observed case.

The impacts of the artificial cold pool in this simulation show the likely importance of the preexisting outflow boundary in the observed case (in addition to the
base-state thermodynamic and wind profiles). We also reran this simulation without including the broad initial cold pool. We found that simulations that included the cold pool had much closer correspondence to the observed case than simulations that omitted the cold pool. The simulation without a cold pool produced no substantial linear structures. Also, without the added cold pool, it was not possible to reproduce the behavior of the observed quasi-stationary Deshler and Superior supercells (which did indeed develop along the preexisting outflow boundary; section 2c).

2) ADDITION OF A MERGING STORM

Observations suggested that cell mergers were important in the evolution of the 22–23 June squall line. Therefore, following up the previous simulation, a fifth warm bubble (referred to as E) was placed in the domain southwest of warm bubble D (Fig. 9b), so that it would move northeastward and collide with storm D, which anchored itself to the outflow boundary. It was hypothesized that the addition of a storm merger would aid in the reorientation of the squall line, as was observed on 22–23 June.

The merger simulation evolved similarly to the four-bubble simulation with the −2-K cold pool in the previous section. However, storms A, B, and C completely dissipated by 2.5 h into the new simulation, likely due to the storms being cut off from the moist low-level air from the addition of the storm E. Storm E was initially identical to the warm bubble storm in the simple simulations [section 3b(1)]. However, after 2 h, storm E’s interaction with storm D changed both storms’ characteristics and subsequent patterns of evolution.

Around $t = 2:10$, the cold pool from storm E’s left mover merged with storm D, which was anchored on the the preexisting outflow boundary. The enhanced convergence and subsequent upward motion resulted in a new third storm between D and E. As these three storms merged, the amount of precipitation they produced increased thus maximizing the local rain rate in time, and causing it to far exceed that in the previous no-merger simulation. The increased local rain rate produced local rainfall exceeding 140 mm (not shown) following the merger. The enhanced rainfall and subsequent evaporative cooling helped to develop a stronger and deeper cold pool under these storms compared to the cold pool that had developed in the no-merger simulation at the same time. Due to this stronger and deeper cold pool, the eastern half of the squall line eventually began to move southward (southward displacement on the east side of line in Fig. 13), much as in the observed nocturnal event (section 2d). These results support the hypothesis that the merger of storms into the Superior supercell enhanced the precipitation production, increasing the cold pool depth and strength, and acting to develop and reorient the 22–23 June storms into an east–west squall line that moved slowly southward.

**FIG. 11.** Simulated reflectivity (shaded) and potential temperature perturbation (−2 K, black contour) at the surface from the simple cold pool simulation at $t = 2$ h.
We also reran the merger simulation without including the broad initial cold pool. The simulations that included the cold pool again had much closer correspondence to the observed case than those that omitted the cold pool. The simulation without a cold pool produced a convective system that was less linear, with a good deal more sporadic convection to its north and east associated with longer-lived remnants of storm splits.
Also, the lack of an initial boundary to anchor storm D caused the eventual storm merger to be less prolific in terms of precipitation and outflow production. As before, we conclude that the preexisting outflow boundary on 22–23 June was an important part of the subsequent evolution.

d. Artificial nocturnal cooling

The final experiment was undertaken to study storms’ possible responses to nocturnal radiative cooling such as was present during the 22–23 June episode. To study the two observed modes of convection (supercell versus squall line), we reran both the isolated warm bubble and merging storm simulations. Both rerun simulations included artificial cooling of the lowest layers using the method described by Parker (2008). The cooling was applied until a surface temperature deficit of $-6.5$ K was reached (corresponding to the nocturnal temperature minimum in the observed case). The net effect of the cooling was to create an isothermal layer extending from the surface up to roughly 900 m AGL. The time of cooling onset was chosen so as to allow the convection of interest to mature first; we began it at $t = 1$ h in the warm bubble simulation, and at $t = 3$ h in the merging storm simulation. The rate of cooling was set at $-3$ K h$^{-1}$ in the warm bubble simulation (following Parker 2008); the rate of cooling was set at $-5$ K h$^{-1}$ in the merging storm simulation in order to fully cool the environment and provide suitable time for analysis before the simulated squall line began to be contaminated by other spurious convection in the model simulation. Although these cooling rates exceed what is commonly found at night in nature, they facilitate analysis of the net impacts of stabilization on the simulated convection during the time that it most closely resembles the observed case, while simultaneously conserving on model run time. To assess the source levels for air within the convective updrafts, two passive tracers (initialized from 0 to 500 m and from 500 to 1500 m AGL) and numerous massless parcel trajectories were introduced and integrated.

1) COOLING APPLIED TO WARM BUBBLE SIMULATION

The first nocturnal simulation was initially identical to the original simulation with one warm bubble. In the original warm bubble simulation, the first storm evolved from a supercell to a squall line as the cold pool formed and grew in size; however, many of the updrafts within the squall line continued to be supercellular. After the onset of the low-level cooling at $t = 1$ h, the evolution and structure of the storms changed. The chilling meant that the parts of the cold pool with a potential temperature perturbation of $-6$ K or higher were no longer cooler than the environment. Following the chilling, the cold pool at the surface was much weaker and was only located directly under the convective line. As the simulation continued, the squall line broke into two parts:
one moving toward the northeast (which eventually dissipated) and a stronger one moving southeastward (Fig. 14a). It was assumed that, after cooling the boundary layer, the convection would evolve into a completely elevated system, feeding on air parcels originating above the lowest 1 km. However, even after the chilling was added, tracers and parcel trajectories showed that the updrafts continued to have air from the lowest 500 m within them (Fig. 14b).

While the weakened surface cold pool continued to lift air, it was not the only source for lift. The squall line also continued to have quasi-supercellular, rotating updrafts throughout the simulation that aided in lifting air into the updrafts via the vertical perturbation pressure gradient acceleration (Figs. 14a,c). The low-level pressure maximum in Fig. 14c is due to the cold pool at the surface. The upper-level pressure minimum is due to a combination of the dynamic pressure anomalies associated with the downshear side of an updraft and with the localized vorticity of the mesocyclone (Klemp 1987; Weisman and Rotunno 2000).

Even though minimal tracer amounts indicate that much of the air in the simulated updrafts originated from above 500 m AGL, the weak concentration shows that low-level parcels were also lifted from the lowest levels by the perturbation pressure gradient acceleration (Fig. 14c). In short, the idealized simulation supports the idea that isolated quasi-supercellular storms within the 23 June environment would be able to survive and remain at least partly surface based, through a combination of cold pool and rotationally induced lifting. This may explain the observed nighttime tornado production in north-central Kansas in spite of the low-level stability in that region (e.g., Fig. 7).

2) COOLING APPLIED TO MERGER SIMULATION

The second nocturnal simulation was initially identical to the original merger simulation. As in the original simulation, mergers caused the reorientation of the storms into an east–west squall line about an hour before the cooling was added (Fig. 15a). After the onset of the low-level cooling at \( t = 3 \) h, the updrafts in the nocturnal merger simulation weakened in time, becoming less intense than those in the original simulation as well as the similar simulation without nocturnal cooling (not shown). However, near-surface air was still able to reach its LFC with the strong vertical lifting provided by the deep cold pool (Fig. 15b). Although the cold pool was only 2 K colder than its environment at the surface, there was a dome in the isentropes that was roughly 2 km deep (Fig. 15b). Consequently, air in the lowest levels glided up the isentropes and flowed rearward over the cold pool,
where some of the air reached its LFC and ascended in convective updrafts. Tracers and parcel trajectories originating in the lowest 500 m were present in a majority of the updrafts, well into the midlevels of the storms (Fig. 15b). Although this simulation is highly idealized, the 2-km-deep cold pool is reminiscent of the 2-km-deep outflow observed by the TOP radar on 23 June (Fig. 8b). Within our nocturnal simulation, the artificial chilling did not have a large impact on the southward-propagating squall line. The squall line remained surface based throughout the experiment and propagated at a similar speed to that in the original merger simulation. Our interpretation is that, on the night of 22–23 June as in our nocturnal experiment, the squall line’s cold pool was able to keep lifting low-level air to its LFC despite its increased CIN and decreased CAPE.

e. Synthesis of idealized simulations

The progression of idealized numerical simulations was designed to isolate the most important processes that governed the observed storms on 22–23 June 2003. With simple initial triggers, the environment favored the development of supercells, with subsequent evolution toward a northeast–southwest-oriented squall line, much as was observed. The addition of a preexisting outflow boundary enabled storms to anchor to it, and was apparently necessary to explain the propensity of the observed storms to deviate from the mean northeastward storm motion, and remain long lived. The addition of simulated storm mergers caused a southward-propagating east–west squall line, suggesting that the observed storm mergers were a fundamental contributor to the evolution of the 22–23 June case. Finally, when the low levels were artificially chilled, the simulated convection continued to be at least partly surface based due to its quasi-supercellular updrafts and the squall line’s deep, strong cold pool. This result, along with the observations reviewed in section 2, lead us to conclude that both the northeastward-moving supercells and the southward-moving squall line of 22–23 June could have been at least partially surface based during much of the night.

4. Conclusions

This study utilized observational data and idealized simulations in order to understand the processes that occurred during the nocturnal convective episode of 22–23 June 2003. Here, we summarize our primary observational findings, and the related interpretations that were supported by the idealized simulations.

- The observed supercells developed along a preexisting outflow boundary. This boundary did more than simply initiate the supercells. The outflow boundary was also important because the supercells could anchor to it, leading to large rainfall totals and facilitating subsequent cell mergers.
- Storm and outflow mergers were fundamental to the reorientation of the system into an east–west squall line. The mergers in particular caused an increase in precipitation production and a subsequent increase in the cold pool strength. In turn, the cold pool was responsible for the slow southward propagation of the squall-line system.
- In addition to the supercells that were initiated along the preexisting outflow boundary, supercells were initiated along the dryline in north-central Kansas. These storms moved northeastward throughout the remainder of the event owing to the southwesterly mean cloud-layer wind.
- As the boundary layer cooled during the night, the two distinct storm modes (supercells and squall line) persisted. Our simulations suggest that these storms were quite possibly able to remain surface based because of their unique mechanisms for lifting low-level air through the large nocturnal CIN and up to the LFC. The simulated southward-moving squall line was sustained by deep cold pool lifting. The simulated northeastward-moving supercells were sustained by their enhanced vertical perturbation pressure gradient acceleration.
- As evidenced by a number of observed nocturnal tornadoes on 22–23 June, it is important for operational forecasters to be aware that nocturnal thunderstorms may in fact be at least partially surface based, thus continuing the threat for severe weather.

The initial motivation for this study was our interest in the degree to which nocturnal storms become elevated, and how this affects their associated likelihood of producing severe weather. The 22–23 June 2003 case was particularly intriguing because it included two distinct modes of convective organization, each with a unique motion vector. This study has primarily addressed the basic mechanisms responsible for producing those two convective modes, and their subsequent response to simple nocturnal-like low-level cooling. Future advances may be possible through the use of more sophisticated case study simulations, especially if dynamic data assimilation can be used to provide a more constrained depiction of nocturnal storms and their low-level environments. Even so, it will likely remain a significant challenge to clearly assess the low-level stability and comparative efficacy of low-level convective lifting in nocturnal regimes, during field experiments much less on a routine basis. Until such information is available
operationally, we generally recommend that forecasters be aware of the possibility that many nocturnal convective events are not entirely elevated. Despite the challenges, it is an important long-term goal to improve our understanding of when and how storms remain surface based at night. This understanding can then be translated into more thoughtful forecasts of severe weather, and warning operations.
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