P1.2 MERGERS BETWEEN ISOLATED SUPERCELLS AND QUASI-LINEAR CONVECTIVE SYSTEMS: A PRELIMINARY STUDY

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1. INTRODUCTION

Past research within the convective storms community has often viewed supercell thunderstorms and larger-scale quasi-linear convective systems (QLCSs, commonly referred to as "squall lines") as distinct entities to be studied in isolation. While this has lead to immeasurable advances in the understanding of supercells and squall lines it overlooks the fact that these organizational modes can be found occurring simultaneously, in close proximity to each other (e.g. French and Parker 2008), often resulting in the merger of multiple storms. While the basic concept of mergers between convective cells has been studied at great length (e.g. Simpson et al. 1980, Westcott 1994), a number of questions remain regarding the processes at work when well-organized convective storms merge and interact. Of particular interest is what this might mean in terms of the production of severe weather including large hail, damaging wind, and tornadoes. With this in mind, the present study provides a first step in an investigation of the dynamics that govern mergers between supercells and QLCSs, through a review of several merger cases.

2. BACKGROUND

Past work on interactions between supercells and other storms, including other supercells, single or multi-cellular storms, and squall lines have lead to an ongoing debate as to whether mergers favor or hinder supercellular organization and tornado production. Modeling studies by Bluestein and Weisman (2000), Finley et al. (2001), and Jewett and Wilhelmson (2006) have suggested that mergers can be detrimental to long-lived supercell structures, with enhanced precipitation causing strong cold pools and evolution towards linear modes. Non-favorable mergers have been observed in actual cases as well. In the case discussed by Knupp et al. (2003) two different supercell storms were observed to permanently lose supercellular characteristics following mergers with a left-moving split from an earlier storm. In a similar case, Lindsey and Bunkers (2005) examined a merger between a left-moving supercell and a tornadic right-mover, finding that the merger appeared to disrupt the circulation of the right-mover and temporarily suspended tornado production. Furthermore, in a study examining long-lived supercells, Bunkers et al. (2006) listed "the supercell merges or interacts with other thunderstorms which can either destroy its circulation or cause it to evolve into another convective mode" as one mechanism for supercell demise, however they also pointed out that "not all storm mergers were destructive". Indeed, Lee et al. (2006) observed that as many of 60 % of cell mergers observed in the 19 April 1996 case resulted in increased cell rotation, and 54% of the tornadoes on this day occurred within 15 minutes of a merger. Thus the impact of cell mergers on supercell longevity is far from certain.

This uncertainty carries over to cases of supercell-squall line mergers as well. A number of cases cited in the literature pertain to events wherein a merger between a squall line (often exhibiting bow-echo characteristics) and a supercell facilitates tornadogenesis (e.g Goodman and Knupp 1993; Sabones et al. 1996; Wolf et al. 1996, Wolf 1998, and LaPenta et al. 2005). In many of these cases the supercell is observed to remain coherent following the merger, with the merged system taking on a "comma" or "S"-shaped reflectivity pattern (Sabones et al. 1996, Wolf 1998). This is considered by some to be a surprising result, as the expectation would be that the outflow from the squall line would undercut the supercell's updraft and disrupt its mesocyclone (Wolf 1998). Indeed, other cases appear to exemplify this more "expected" behavior whereby bow-echo supercell mergers lead to a rapid decrease in supercell organization, (Calianese et al. 2002). This sometimes even occurs within an event where favorable interac-

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tions were also observed (Wolf et al. 1996). Adding complexity to this debate is the frequently observed increase in both storm strength and rotation *prior* to storm mergers, suggesting that the two storms may be interacting in some way before they actually merge (Przybylinski 1995; Wolf et al. 1996; LaPenta et al. 2005).

In short, a survey of past research reveals cases where squall line-supercell interactions lead to an enhancement or at least persistence of supercell structures, as well as those that appear to destroy preexisting supercell structures. In the cases where the supercell is able to persist, several cases suggest that tornadogenesis is instigated by the merger (e.g. Goodman and Knupp 1993; Sabones et al. 1996). While this dichotomy of behaviors has been well documented in the literature, it remains unclear as to why some mergers favor sustained supercell structures, while other destroy them. The present study looks address this by delving deeper into the dynamic processes at work during merger events. This paper outlines the first step in achieving this goal, focusing on identifying key characteristics of these merger events, both via an examination of past literature, as well as through analysis of new cases. This will set the stage for numerical simulations, which will provide a means to examine the dynamic processes at work during these mergers, aiming to provide better insight as to what may cause a supercell-squall line merger to be favorable vs unfavorable for the supercell's circulation.

3. METHODS

This work utilized operationally available data from across the continental United States. Cases were identified using a combination of the Storm Prediction Center's Online Severe Thunderstorm Events Archive (http://w1.spc.woc.noaa.gov/exper/archive/events/) and the NCAR MMM Online Image Archive (http://www.mmm.ucar.edu/imagearchive/) to search for events that featured isolated supercells and squall lines between January 2000 and June 2009. Initially, the search domain focused solely on Oklahoma, in the interest of being able to exploit a larger number of observational datasets. However, in the interest of increasing the number of cases, other events from around the country were included as well. These latter cases were identified from past investigations of multi-mode (squall line and supercell) cases done by the first author, rather than through a systematic search related to the present work. An initial list of 63 cases, was narrowed to 16 "most promising" cases for which

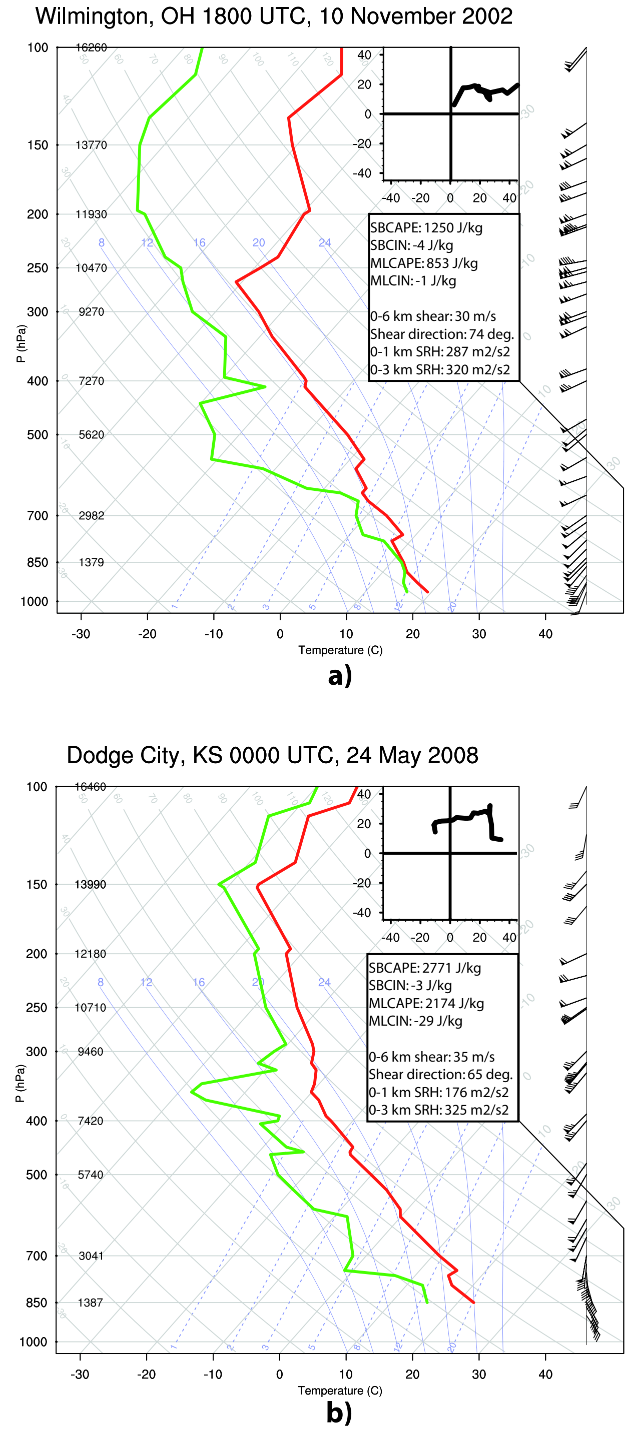

Figure 1: Skew-T log-P diagrams and hodographs representing the background environments for the four cases presented: a) 10 November 2002 1800 UTC sounding from Wilmington, OH, b) 24 May 2008 0000 UTC sounding from Dodge City, KS, c) 11 February 2009 0000 UTC sounding from Fort Worth, TX, and d) 19 April 2009 0000 UTC sounding from Lamont, OK. Hodographs for the tropospheric wind profile are included in the upper right corner of each sounding, along with a wind profile, both of which are in units of m/s (half barb = 5 ms, full barb = 10 ms, flag = 25 ms. Calculated surface based (SB) and 100 mb mixed layer (ML) CAPE and CIN are provide for each sounding, along with 0-6 km bulk shear and 0-1 and 0-3 km SRH.

Level II WSR-88D single site radar data were obtained. An initial analysis of the Level II data further narrowed the list to 8 archetypal cases that contained well-organized supercell and QLCS modes that merged during their lifetimes. Other factors including availability of radar data throughout the event, and proximity to the radar were also taken into account in finalizing case selection.

For the initial analysis presented in this work, base reflectivity and base velocity WSR-88D data were examined for each case to provide an overview of storm evolution before, during and after the merger(s) between the squall line and supercell(s) of interest. In addition, a general picture of the background environment was ascertained using operationally available surface and upper air observations and archived SPC Mesoanalysis graphics (for events after 2006, Bothwell et al. 2002). Finally, data from the NCDC Storm Data archive (http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwEvent~Storms) were also used to provide details on instances of severe weather (namely tornadoes) that occurred in conjunction with the storms involved in the merger.

4. CASES

In the interest of providing more detail, a sub-set of 4 of the more representative cases will be presented in this paper. These cases were selected as they illustrate several key commonalities seen between all 8 cases, while also each also serving to illustrate a unique characteristic of interest. A short summary of each case will be provided below, followed by a discussion of some of the common themes identified from the initial analysis of all 8 cases in the following section.

4.1 10 November 2002

10 November 2002 was witness to a widespread outbreak of severe weather and tornadoes across the eastern half of the United States, from the Great Lakes to the Gulf Coast. The present analysis will focus on the early part of this event, particularly the interaction between a supercell and squall line in western Ohio. The synoptic environment was characterized by a strong, negatively tilted upper-level trough over the central United States, with an attendant surface low pressure system over northern Michigan and a surface cold front extending from the Great Lakes to the Gulf coast. An 18 UTC sounding from Wilmington, Ohio (Fig. 1a) contained 30 ms^{-1} of 0-6 km shear and 1250 J kg^{-1} of surface-based

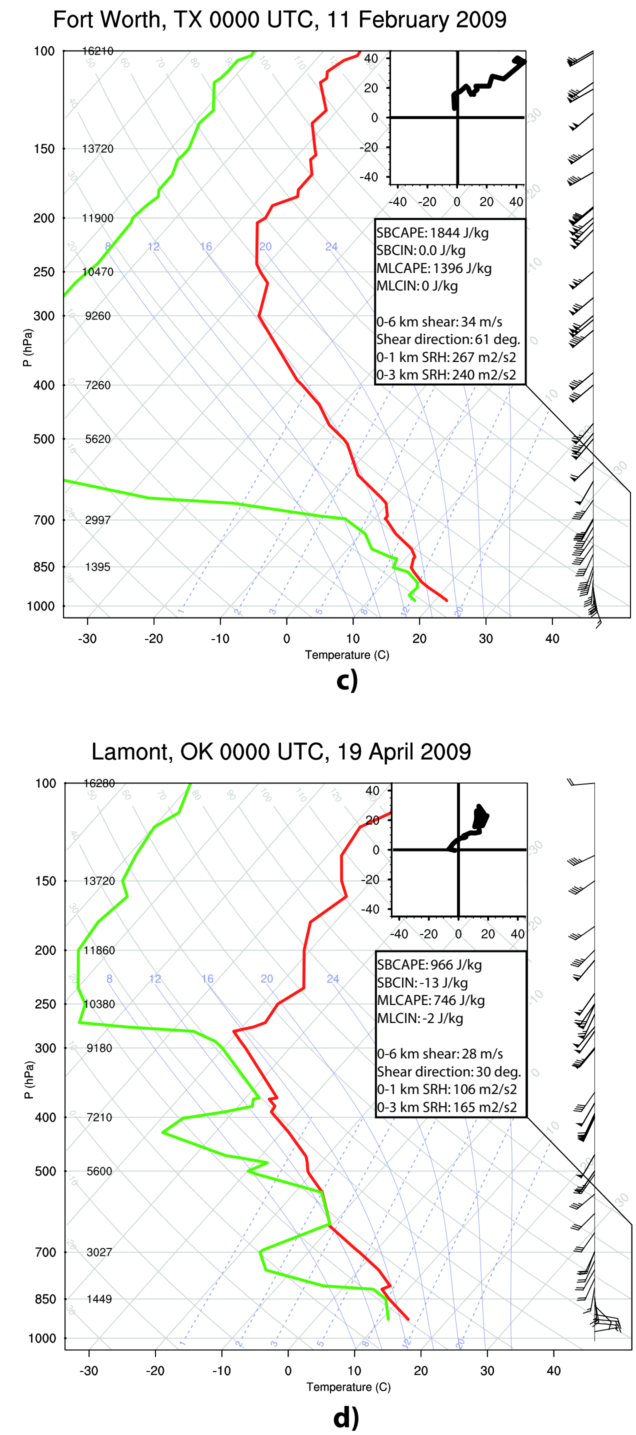

Figure 1: (*Continued*)

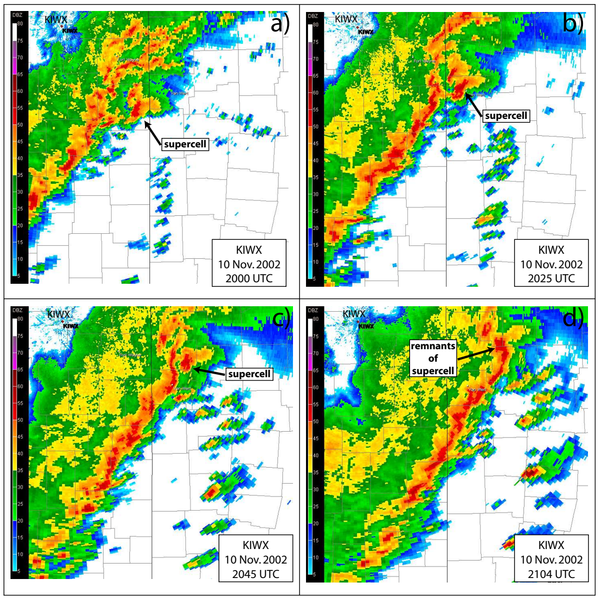

Figure 2: Time series of radar reflectivity images from the North Webster, IN (KIWX) WSR-88D for 10 November 2002. Radar reflectivity is shaded per the color bar on the left of each image, and times are included in the lower-right corner.

convective available potential energy (SBCAPE), favoring supercells (Rasmussen and Blanchard 1998). A 0-1 km storm-relative helicity (SRH) of 287 m^2s^{-2} further favored storm rotation and indicated that tornadoes were possible (Rasmussen and Blanchard 1998).

A squall line began developing along the cold front in central/eastern Indiana during the late morning hours on the 10th and progressed eastward. By 1930 UTC, as the line approached the Ohio/Indiana border, a supercell developed approximately 40 km ahead of the line in eastern IN and raced northeastward, parallel to the line (not shown). A complex interaction between the supercell and line began by approximately 20 UTC (Fig. 2a). North and west of the supercell, the squall line began to weaken and lag in its eastward motion. Meanwhile, extending southwestward from the supercell, the line appeared to surge eastward and intensify (Fig. 2b-c). This overall pattern continued for approximately an hour, with the supercell fully merging with the northern end of the line by 21 UTC (Fig. 2d). During this period, the line surged east of the supercell to its south, however a clear separation between the two remained evident in both the WSR-88D reflectivity (Fig. 2c) and velocity data (not shown). During this same period, the supercell produced a long-track tornado with damage rated at F-4 on the Fujita tornado intensity scale[1]. Following the merger, which appeared to result from squall line outflow overtaking the supercell, supercell characteristics in both reflectivity and velocity data are quickly lost as it is absorbed by the line (Fig. 2d).

4.2 23 May 2008

A widespread severe weather and tornado outbreak occurred across southwestern Kansas on 23 May 2008, consisting of several intense, long-lived supercells two of which eventually merged with a squall line. The background environment strongly favored a supercellular mode, with 35 ms^{-1} of 0-6 km shear, 325 m^2s^{-2} 0-3 km SRH (notably 0-1 km SRH was approximately half that, 176 m^2s^{-2}), and 2771 J kg^{-1} of SBCAPE (Fig. 1b). An intense upper level low to the west, along with a surface dryline and cold front in the region promoted widespread convective initiation. The initial convective mode across western Kansas consisted of multiple isolated supercells, one of which produced an EF-4 tornado in west central Kansas. By 0000 UTC, a squall line began to develop in northwestern Kansas and subsequently grew southward along a north/south boundary. Ahead of this line, isolated supercells continued to be favored, with 3 supercells becoming dominant just east of the developing squall line. Of these, one dissipated as an isolated storm, while the other two merged with the line.

The first of these mergers facilitated a complex storm evolution as it occurred. As the supercell (S1 in Fig. 3a-d) approached the squall line, the line broke northwest of the supercell. S1 merged with the segment of the line south of this break (Fig. 3a-b), producing an EF-2 tornado at the approximate merger time. Following the merger, S1 remained definable in both reflectivity (Fig. 3b-d) and velocity fields for at least an hour, appearing to enhance straight-line winds within the line to the south. Meanwhile, the portion of the squall line north of the break, very rapidly evolved into a supercell (S3 in Fig. 3b-c), developing strong rotation, and producing an EF-2 tornado of its own before eventually dissipating.

The other pre-line supercell (S2 in Fig. 3a-f) continued to persist ahead of the line while the first merger took place (Fig. 3a-d). It moved north and parallel to the line, and produced an EF-3 tornado that was on the ground for 35 km, which was the

[1]Depending on the case both the original Fujita scale (Fujita 1971) as well as the newer, "enhanced" Fujita (EF) scale (McDonald and Mehta 2006) are used to describe tornado damage, based on which was used during the damage survey.

longest track surveyed during the event. Eventually S2 merged with the remnants of S1 at the north end of the line, maintaining its supercellular characteristics for about an hour and enhancing straight-line winds to its south as well (Fig. 3e-f). Notably, the the termination of the tornado damage associated with S2 appears to roughly coincide with the merger, and no further tornado damage was reported with this particular storm following the merger.

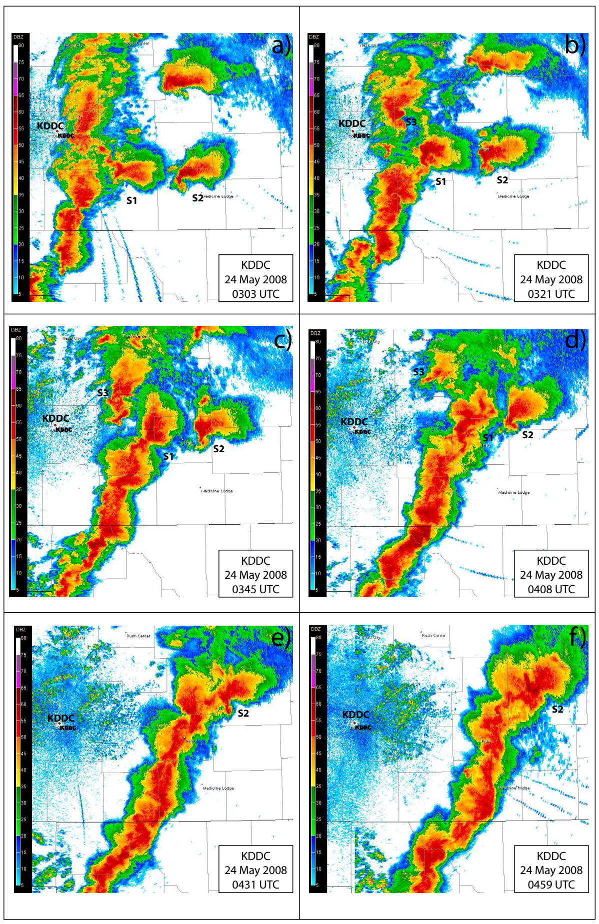

Figure 3: As in Fig. 2, but from the Dodge City, KS (KDDC) radar for the 23 May 2008 case.

4.3 10 February 2009

The 10 February 2009 event was a cold-season severe weather outbreak across central Oklahoma, consisting of several isolated supercells early on, and a supercell that merged with a squall line later in the event. The large scale environment featured strong upper-level dynamics and favorable conditions for supercells (34 ms^{-1} 0-6 km shear, 240 m^2s^{-2}0-3 km SRH, 1844 J kg^{-1} SBCAPE, Fig. 1c), along with a surface cold front that forced the squall line. Early in the event, the dominant convective mode was isolated supercells, several of which produced EF1/2 tornadoes in the Oklahoma City metro area (not shown). Continued convective initiation and cell mergers along a surface cold front eventually lead to the development of a squall line across western Oklahoma. As the squall line matured, a single isolated supercell developed near the Oklahoma/Texas border and moved north into south-central Oklahoma (Fig. 4a). The supercell rapidly intensified and went on to produce EF-2 and EF-4 tornado damage along a 33 mile track prior to its merger with the line (Fig. 4a-c). The line weakened overall prior to the merger, however there was no distinct break as was observed some other cases (Fig. 4c). The supercell maintained its identity following the merger, remaining evident as a region of locally intense reflectivity (Fig. 4c-d) with attendant mesoscale circulation noted in the velocity data (not shown). Additionally, a kink in the the line developed at the approximate location of the merger, with the portion of the line south of the kink being displaced further east after the merger took place (Fig. 4d). There was no further tornado activity following the merger.

4.4 18 April 2009

The final case, 18 April, 2009 differs from the others in that it was not associated with a widespread severe weather outbreak. Rather, it consisted of a localized event in north central Oklahoma consisting of a supercell and squall line that developed nearly concurrently and merged shortly thereafter. The synoptic environment was characterized by a broad upper level trough over the central plains with a surface low-pressure center located in north-central Oklahoma and cold front extending to the southwest. The 0000 UTC sounding from Lamont, Oklahoma (Fig. 1d) suggests an environment supportive of supercells with 28 ms^{-1} of 0-6 km shear and 966 J kg^{-1} of CAPE. Additionally, 0-1 and 0-3 SRH were comparatively weaker than in the other cases (106 and 165 m^2s^{-2}respectively) which may explain the lack of tornado production associated with this case.

An isolated supercell developed just ahead of a cluster of cells that rapidly began evolving into a small line (Fig. 5a). As both features continued to organize they began to merge, with the line ostensibly overtaking the supercell from behind (Fig. 5b). The merger occurred just as the supercell's mesocyclone appeared to be strengthening and the circulation contracting, however it weakened considerably as the merger took place, only to re-emerge as a strong, but broader circulation shortly thereafter (not shown). This circulation, located at the north end of the developing line, appears qualitatively similar to a book-end vortex (e.g. Weisman 1993, Weisman and Davis 1998, Atkins et al. 2004), featuring both a broad, strong rotation as well as a spiral pattern in the reflectivity field (Fig. 5c). Straight-line winds increased to the south of this circulation (based on Doppler velocities) and bowing of the convective line was evident within the reflectivity field in this region as well (Fig. 5c). This feature persisted for over an hour as the line intensified and progressed across central OK (Fig. 5d). Of particular interest in this case is the relative youth of both systems at the time of the merger, as they developed concurrently and then merged within approximately 1 hour of initial development. This is compared to some of the other cases wherein the supercell and/or squall line evolved individually for a long period prior to merging.

5. COMMONALITIES BETWEEN CASES

The primary motivation for this initial study was to examine a number of squall line-supercell merger cases to determine useful areas of focus for future, more detailed analysis and study. With this in mind, several common features that stood out between the 8 case examined are summarized below.

- In just about every case, the supercell remains identifiable for at least an hour following the merger, and appears to have a significant impact on the evolution of the squall line. This would tend to suggest that the supercell, rather than the squall line "dominates" the merger. As noted by Wolf (1998) this is a somewhat surprising result as the squall line's outflow appears to have little impact in terms of disrupting the mesocyclonic circulation of the supercell.

- In some cases the merger is preceded by a split or break in the line, which may play a role in promoting the longevity of the supercell following the merger. In what is perhaps an extreme case, on 23 May 2008 this appeared to facilitate the development of a new supercell within what had been the northern portion of the line.

- Post-merger evolution appears to vary based on where along the squall line the merger occurs. For mergers that occurred approximately halfway along the squall line, a break in the line sometimes preceded the merger, however the line maintained its structure and intensity north and south of the merger. The characteristics of the supercell, including a cyclonic circulation, were maintained, and generally became embedded within the line following the merger. When the merger occurred closer to the north end of the line, a weakening of the line north of the merger was often observed, and typically the remnants of the supercell subsequently became the northern end of the intense convective line. In this scenario, the supercell mesocyclone often further evolved into a broader cyclonic circulation that appears at least qualitatively similar to the "bookend vortices" described by Weisman (1993), Weisman and Davis (1998), and Atkins et al. (2004).

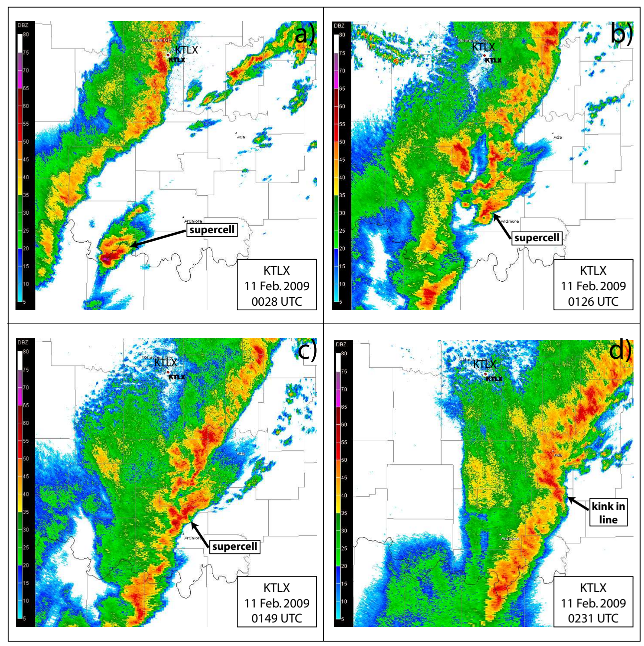

Figure 4: As in Fig. 2, but from the Oklahoma City, OK (KTLX) radar for the 10 February 2009 case.

- Given the apparent persistence of supercell circulations following the merger, it is of interest to examine their vorticity source. Does the circulation continue to ingest and tilt horizontal vorticity from the background environment, or is it able to feed off baroclinically generated vorticity from the squall line's cold pool? In this regard, it would be useful to explore the similarities between the circulations that result from a supercell/squall line merger, and the mesovorticies that are sometimes observed within squall lines absent such a merger (e.g.

Weisman and Trapp 2003; Trapp and Weisman 2003; Wakimoto et al. 2006).

- In most of the cases where tornadoes were present, the longest-track (and in some cases most intense) tornadoes of the event were produced by supercells that evolved for a prolonged period ahead of, but in close proximity to the squall line. For the most part these path lengths were at least twice those produced by isolated storms. It should be noted that the large scale environment was favorable for supercells/tornadoes (i.e. large shear/SRH), and other tornadoes were present in most cases, however the longest track storms were commonly associated with a pre-line supercell. This, in addition to past observations of storm intensification as supercells and squall lines converge (e.g. Przybylinski 1995; Wolf et al. 1996; LaPenta et al. 2005), suggest that the storms are having an influence on one another prior to merging. One possible hypothesis to this end is that the squall line is altering the pre-line environment in a manner that favors supercell intensification/long-lived tornadoes.

- These cases contained instances where a merger appeared to instigate tornadogenesis or at least maintain an ongoing tornado as well as instances where the merger appeared to either terminate an ongoing tornado, or failed to instigate tornadogenesis. This would suggest, as seen in the past literature, that mergers do not clearly favor or hinder tornadogenesis, but rather the details of a given merger event may determine if a tornado will form, the specifics of which are not clearly understood.

6. FUTURE WORK

The case studies presented herein represent the first step in a much more in-depth study of mergers between squall lines and supercells. Subsequent work will focus on delving deeper into these cases to examine the underlying dynamics at work within these types of events. To accomplish this, we plan to exploit available observations to the fullest extent possible, while also using numerical simulations, as these may provide the best means for addressing some of the hypotheses outlined in the previous section. This is especially true with regards to isolating some of the dynamic processes at work. We intend to utilize a combination of idealized simulations for specific, controlled hypothesis testing, while also employing case-study simulations to provide a means of further analyzing specific cases and bridging the gap between observations and the idealized simulations. Given their inherent complexity (i.e. the presence of multiple convective modes), advanced techniques such as the use of data assimilation, non-homogeneous idealized base-state conditions, and idealized representation of persistent linear forcing mechanisms are likely to be necessary to accurately simulate these types of events.

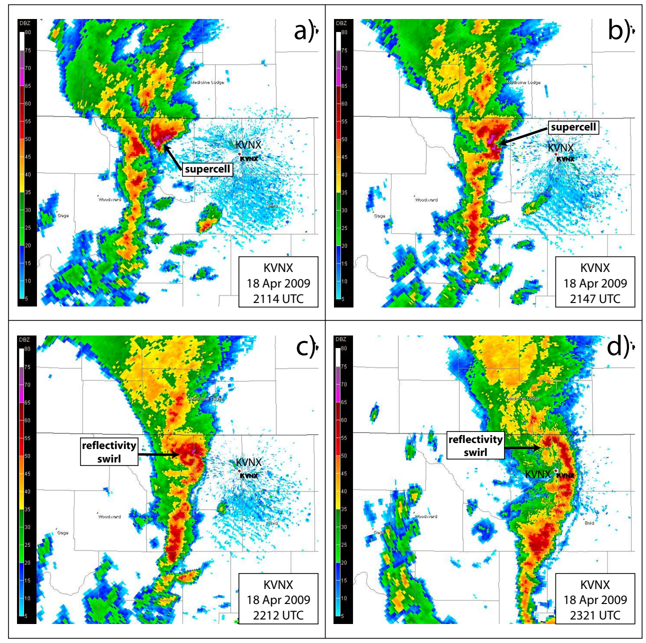

Figure 5: As in Fig. 2, but from the Vance Air Force Base, OK (KVNX) radar for the 18 April 2009 case.

Acknowledgments

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