AN INVESTIGATION OF STORM MORPHOLOGY AND MESOVORTEX EVOLUTION WITHIN A MIDWESTERN QUASI-LINEAR CONVECTIVE SYSTEM USING CONVENTIONAL AND SINGLE-DOPPLER RADAR DATA

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Abstract

In the morning hours of 29 June 1998, a line of severe convective storms traversed central Iowa, producing a wide swath of straight-line wind damage (several gusts exceeding 50 m s-1) and isolated weak-to-moderate intensity tornadoes (F0-F2). This quasi-linear convective system evolved into a severe squall line with three high-precipitation (HP) supercells and multiple well-defined mid-level mesocyclones embedded within it. Although scattered wind damage was reported across many sections of the entire line, this paper focuses on the evolution of one particularly active portion associated with a nearly continuous swath of severe straight-line winds and tornadic activity beginning 40 km northwest of Des Moines and extending through the metropolitan area.

One of the embedded HP supercells contained several mid-level rotating centers that exhibited descending vortex characteristics between 1716 and 1806 UTC; their strongest cyclonic shears persisted at mid levels of the circulation. As the storm approached the Des Moines metropolitan area between 1806 and 1833 UTC, the outflow-dominated HP supercell further matured and several non-descending tornadic and non tornadic mesovortices occurred along a very progressive outflow boundary.

The evolution of the near-storm vertical wind shear likely played a role in the system's intensification and transition from a supercellular to a linear structure. Weather Surveillance Radar–1988 Doppler (WSR 88D) data from the NOAA/National Weather Service (NWS)/Weather Forecast Office (WFO) Des Moines are used to document the storm reflectivity and velocity structures as the storm approached the Des Moines area. Time height rotational velocity (Vr) traces are used to show the characteristics of the circulations and illustrate the differences

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between the tornadic and non tornadic vortices. Specifically, we found that several deep vortices near the northern flank of the HP supercell appeared to be responsible for enhancing the mesoscale rear inflow and convective scale outflow. As the outflow accelerated, several non supercell tornadic and non tornadic vortices, which initially developed from low levels, rapidly deepened and intensified. One of these non-descending vortices was responsible for the tornadic activity northwest of Des Moines.

1. Introduction

During the early afternoon of 29 June 1998, a severe quasi-linear mesoscale convective system (QLCS) traversed central Iowa producing widespread straight-line wind damage (gusts exceeding 50 m s^{-1} and several weak to moderate intensity tornadoes (F0-F2) (Fig. 1).

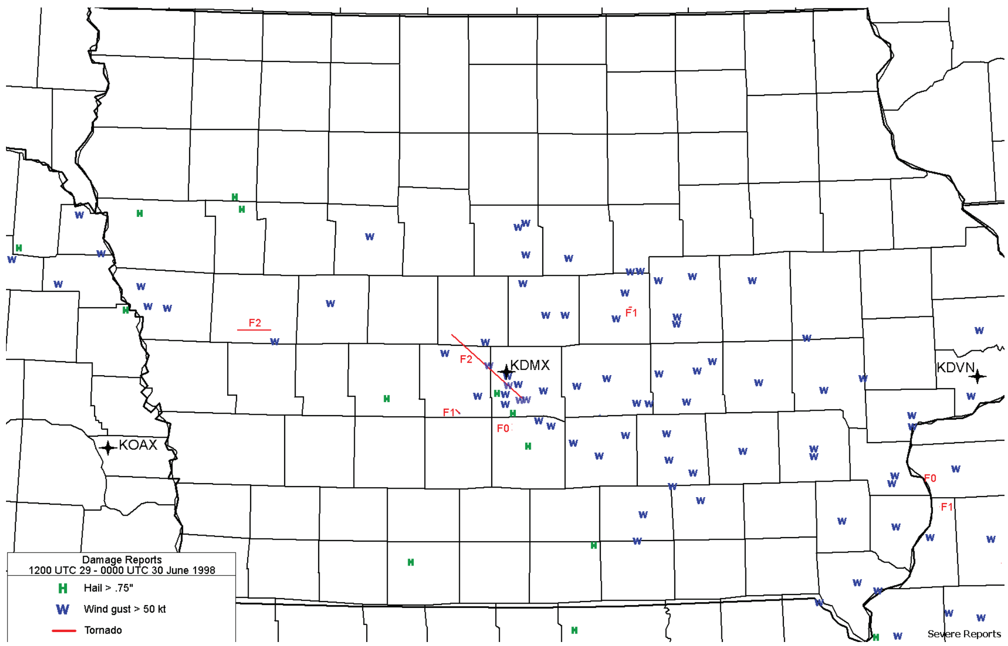

Fig. 1. Severe weather reported between 1200 UTC 29 June 1998 and 0000 UTC 30 June 1998 (NCDC 1998). The WSR-88D sites at Des Moines (KDMX) and Davenport, IA (KDVN), as well as Omaha, NE (KOAX), are indicated for reference.

Early in the system's life-time, the overall storm complex contained several embedded high-precipitation (HP) supercells. The proximity to the WFO Des Moines, Iowa WSR-88D provided a wealth of data that allowed for a detailed examination of the kinematic features and storm-scale cyclonic circulations associated with the QLCS during the intensifying and early mature stages of its life-cycle.

This paper examines the reflectivity and mesovortex structure during the intensifying and early mature stage of QLCS evolution (pre-bow echo and early bowing stage). Thus far, a limited number of studies have focused on this portion of a QLCS's lifecycle. Section 2 provides a literature review of convective storm morphology. Section 3 describes the antecedent and coincident upper-air and surface synoptic scale conditions as they played an important role in the development and sustenance of the QLCS. In section 4, Doppler radar data from WFO Des Moines, Iowa (KDMX) are used to describe the complex storm morphology and radial velocity structures as the system approached the Des Moines metropolitan area. Specifically, the evolution of one particularly intense portion of the convective line that contained an HP supercell is examined in detail. This embedded hybrid HP supercell and its associated storm-scale cyclonic circulations were responsible for a nearly continuous swath of severe straight-line wind damage and a moderate intensity tornado (F2). In section 5, the structure of a tornadic mesocyclone in close proximity to the KDMX radar site is discussed. In particular, the low-level velocity structure of the tornadic mesocyclone is examined in detail and the observations are compared with those documented by Burgess and Magsig (1998; hereafter BM98) who examined several tornadic vortices at close range to a WSR-88D radar. Summary and conclusions are presented in section 6.

2. Review of Convective Storm Morphology

The current operational definition of a supercell is a convective storm, which shows a persistent correlation between vertical vorticity and vertical velocity (Weisman and Klemp 1982), that is, a storm that contains a persistent rotating updraft. Moller et al. (1994) presented a set of conceptual models on variations of the supercell theme, advancing the basic model set forth by Browning (1964). In the United States, the classic supercell (Browning 1964) typically occurs in the southern Great Plains; however, occurrences were documented across parts of the northern High Plains, Midwest, southern Gulf Coast, and Northeast. Research has shown that the HP supercell is more common over the Midwest often due to a deeper low-level moisture regime compared to areas across the Great Plains. Heavy precipitation is frequently observed along the trailing side of the mesocyclone with HP storms where other supercell structures are often rain free (Moller et al. 1990; hereafter MDP90). Although these storms may not occur clearly isolated from surrounding convection, they remain distinctive in character. HP supercell reflectivity characteristics often include spiral, banded-like reflectivity structures suggestive of rotation within a region of high reflectivity.

The accompanying mesocyclone often occurs along the storm's forward flank within the inflow region of the HP storm and then migrates rearward into the heavy precipitation core. These types of storms can become efficient hail, wind, and tornado producers. This is in contrast to the rear-flank mesocyclone typically associated with the classic supercell (MDP90). MDP90 also noted that it is quite common for an HP supercell to transition from a classic supercell, or into a bow echo with rotating comma heads.

MDP90 noted that QLCSs and bow echoes may contain HP storms. These storms are frequently observed near and south of the apex of large bowing convective systems. Such storms often exhibit a large kidney-bean shaped reflectivity structure with strong low-level reflectivity gradients observed along the eastern flank signifying the storm's weak echo region (WER). Weak short-lived tornadoes may form in the vicinity of the WER and along the storm's rear flank downdraft. These storms will typically appear as meso-β scale HP storms and comma-shaped echoes within a larger, meso-α scale bowing segment. Isolated as well as HP storms embedded over the southern part of convective lines and bow echoes tend to travel along pre-existing thermal boundaries (Maddox et al. 1980; Markowski et al. 1998). HP storm mesovortices benefit from the solenoidal effects of the thermal contrasts across a surface boundary and the amplified vertical wind shear (VWS) in the vicinity of the boundary.

In the mid 1980s, a number of observational studies (e.g., the PRE-STORM Project; Houze et al. 1989) focused primarily on squall lines in the mature stage of their lifecycle. A synthesis of these observational studies led to the well known conceptual model of a squall line system [see Houze et al. (1989) for details].

Squall lines, which develop into damaging convective systems, typically contain waves along the leading edge. The term "line-echo-wave-pattern" (LEWP) coined by Nolen (1959) showed how one part of the line accelerates, while an adjacent part decelerates, resulting in a sinusoidal mesoscale wave pattern within the larger line. Hamilton (1970) noted the correlation of the accelerated part of the LEWP to damaging straight-line winds and tornadoes. Fujita (1978) used the term "bow echo" to name the bulges or accelerated segments within the larger line. He also deduced that the bulges in the reflectivity pattern were associated with a strong meso-β scale high-pressure center and the crest with a meso-β scale low-pressure center.

Fujita (1978) put forth the first detailed morphological description of the bow echo. His well known conceptual model shows how an initial tall echo evolves into a bow-shaped line of convective cells as strong downbursts descend to the surface. At the time of strongest surface winds, a spearhead echo may form. As the overall system

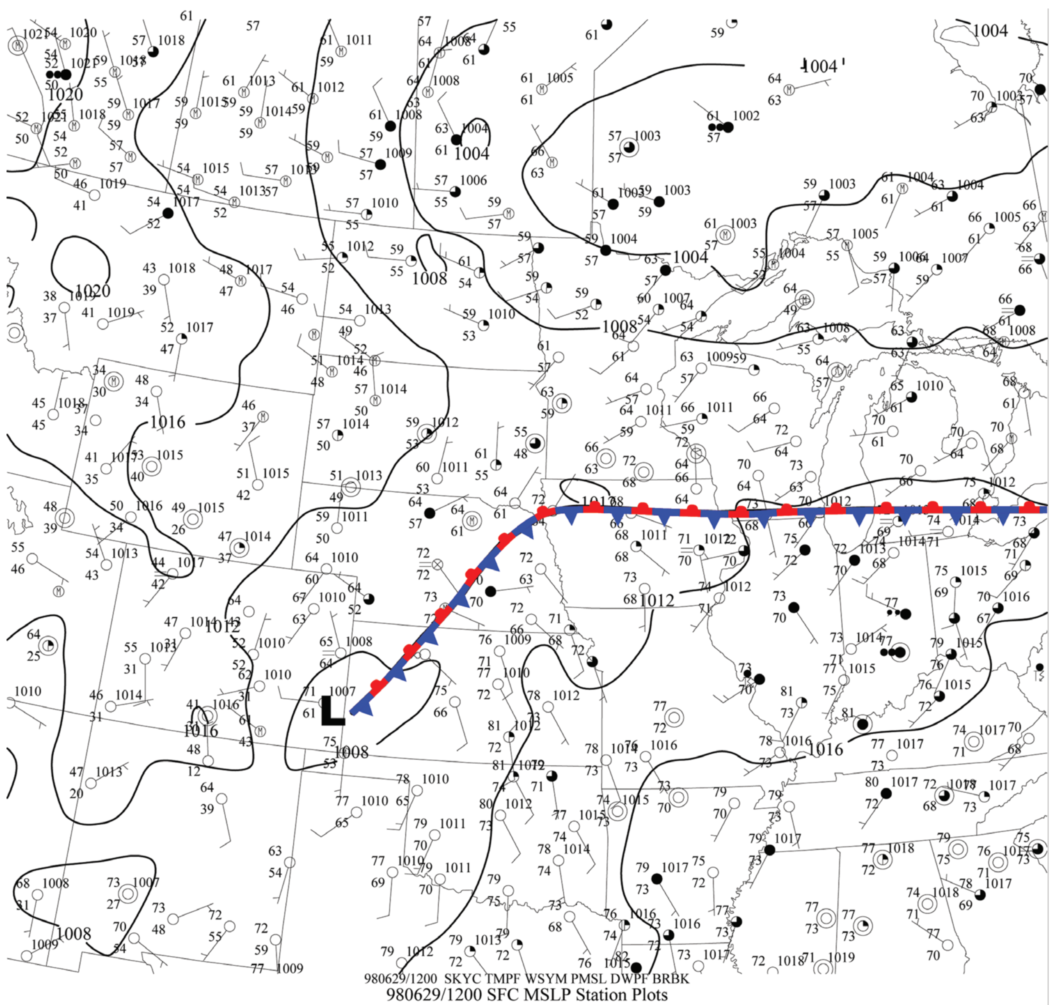

Fig. 2. Station plots and sea-level pressure in millibars (thin solid) valid at 1200 UTC 29 June 1998. Temperatures and dew points are in degrees Fahrenheit and wind barbs are in knots. The degree of cloud cover at each station is indicated by the darkened circles. The location of the stationary front is indicated.

declines, the convective system evolves into a comma-shaped echo pattern with a cyclonically rotating head at the northern end.

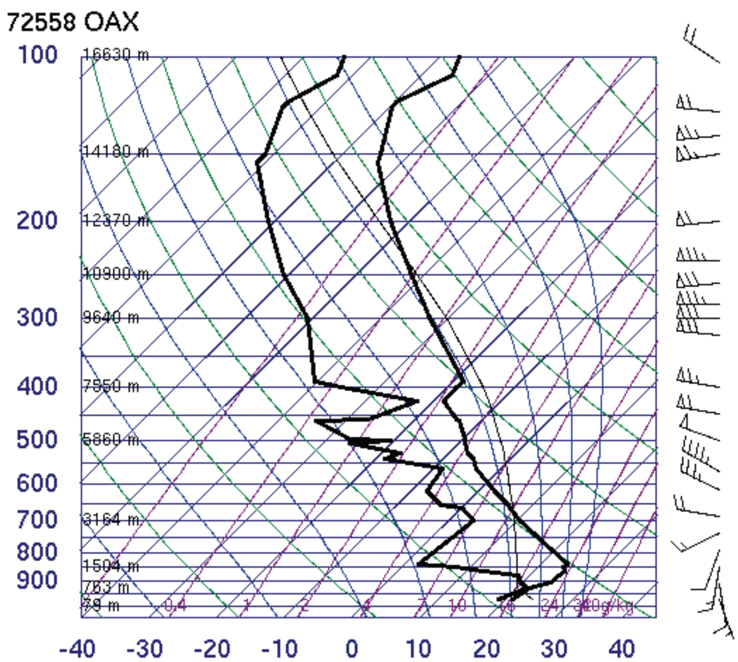

Fig. 3. Sounding valid at 1200 UTC 29 June 1998 from Valley, Nebraska (KOAX).

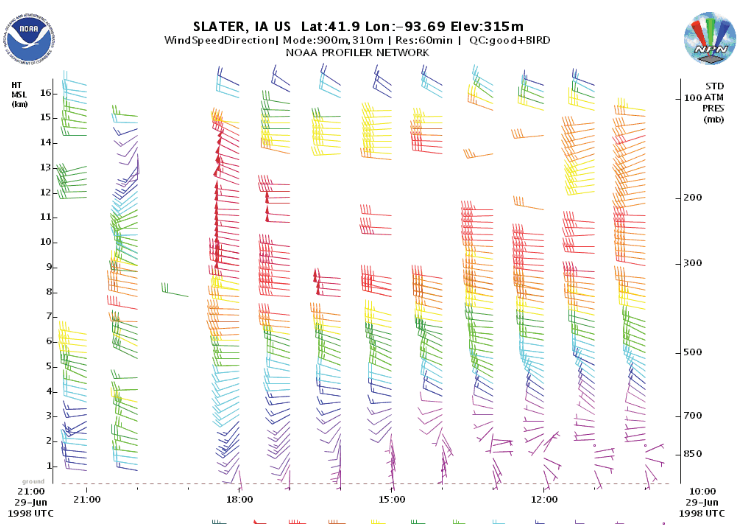

Fig. 4. Wind profiler data from Slater, Iowa. Altitudes on the y-axis are plotted in kilometers and wind barbs are in knots. Data are plotted from 1000 – 2100 UTC 29 June 1998.

3. Synoptic Environment

The pre-convective environment observed on 29 June 1998 over the midwestern portion of the United States was consistent with those associated with warm season "progressive" type derechos (Johns and Hirt 1987). Specifically, this environment is characterized by relatively weak synoptic-scale forcing, northwesterly flow at 500-mb, advection of relatively warm, moist air at 850-mb in the vicinity of the derecho initiation area, and a quasi-stationary boundary at the surface that is typically oriented in the west-east direction. Furthermore, there is likely to be strong instability and moderate low-level unidirectional shear present. In this type of environment, the derecho-producing system develops along and subsequently moves nearly parallel to the existing thermal boundary with some component of motion directed into the warm sector.

The objectively analyzed surface analysis at 1200 UTC on 29 June 1998 is shown in Fig. 2. At this time, a stationary front was extending from an area of low pressure over southern Ontario westward across Michigan and into western Iowa. This frontal feature then connects to a weak low pressure center situated over southwestern Kansas. Warm, moist southerly flow is evident south of the front. Analogous to the "progressive" type derechos described by Johns and Hirt (1987), the QLCS developed in close proximity to the

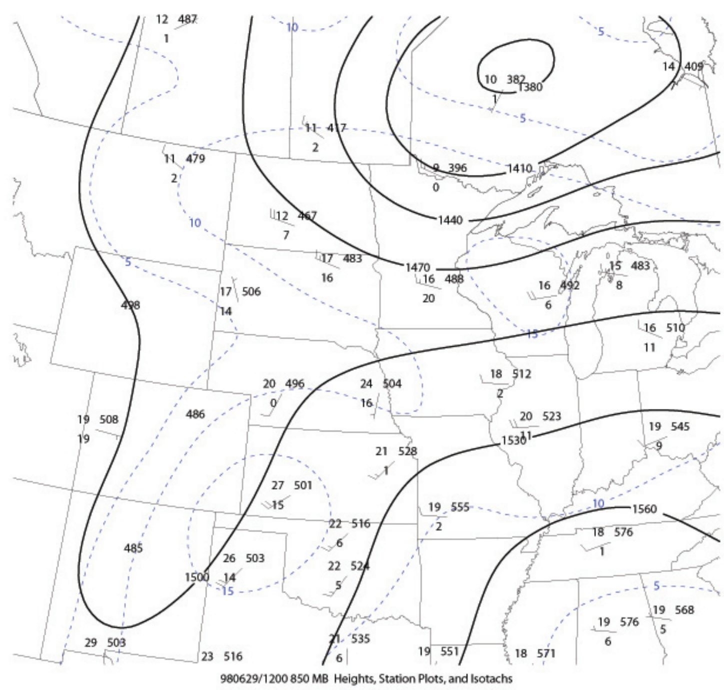

Fig. 5. 850-mb station plots, heights in meters (solid) and isotachs (dashed) valid at 1200 UTC 29 June 1998. Temperatures and dew point depressions are in degrees Celsius. Isotach magnitudes are in knots.

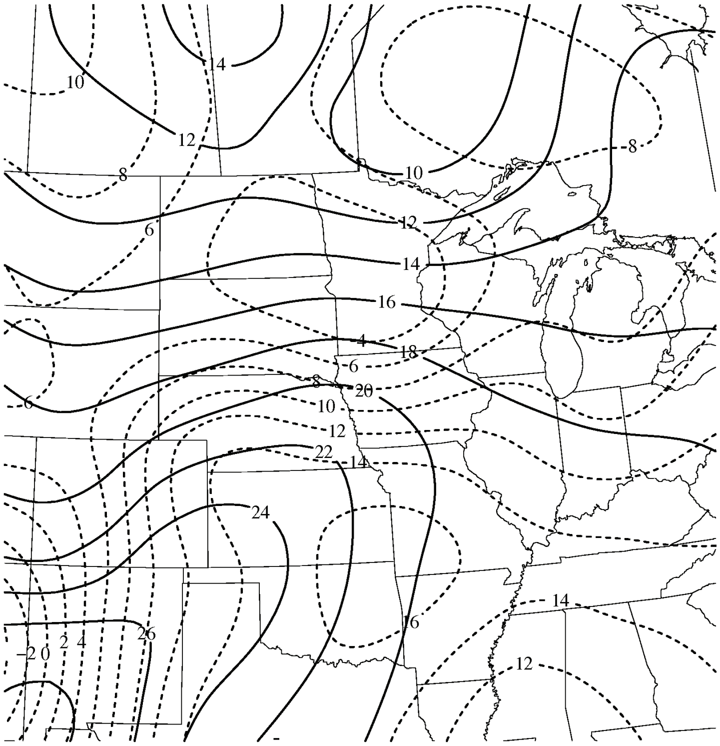

Fig. 6. 850-mb temperature (solid) and dew point (dashed) analyses valid at 1200 UTC 29 June 1998. Temperatures and dew points are plotted in degrees Celsius.

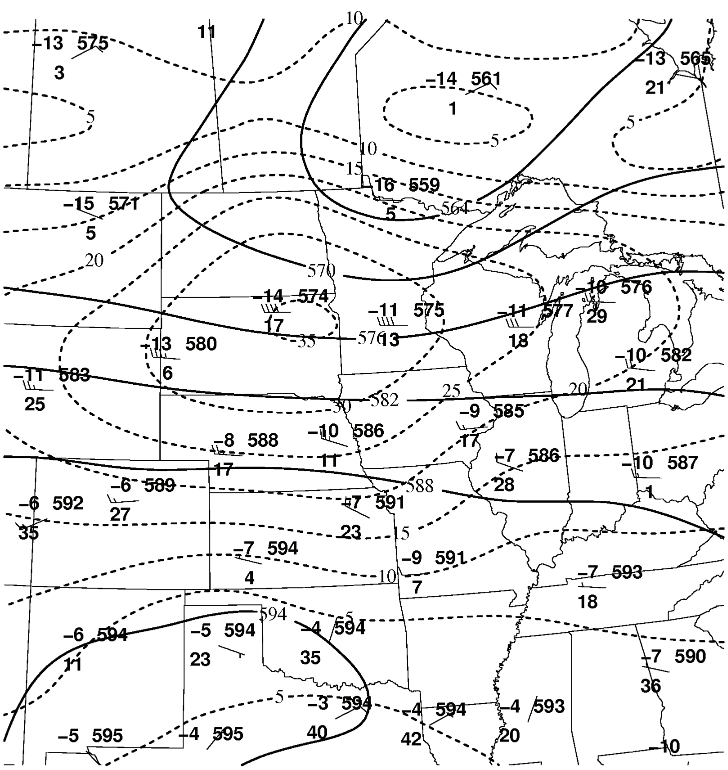

Fig. 7. 500-mb station plots, heights in meters (solid), and isotachs (dashed) valid at 12 UTC 29 June 1998. Temperatures and dew point depressions are in degrees Celsius. Wind barbs are in knots.

stationary front and subsequently moved along it and into the warm sector as it propagated through Iowa.

The 1200 UTC Valley, NE (KOAX) Skew-T analysis on 29 June 1998 (Fig. 3) indicated that deep moisture is present through the lowest kilometer, with sharp drying above. Surface-based convective available potential energy (CAPE) calculated using a forecast maximum temperature (dew point) of 38°C (19°C) yielded a value of 3110 J kg^{-1}. A more realistic CAPE based on an anticipated maximum temperature (dew point) of 29°C (24°C) along and south of the warm front yielded approximately 5120 J kg^{-1} and a Lifted Index of -12°C. Surface to midlevel equivalent potential temperature (θ_e) differences exceeded 30 K, and in combination with large wetbulb temperature differences, this could result in strong evaporative cooling in organized downdrafts that develop. Additionally, there is a nearly-adiabatic layer located between 850 and 500 mb; this is also highly favorable to momentum transport in downdrafts since the atmosphere is not resistant to vertical displacements. The vertical shear profile at KOAX suggests supercells are possible. At 1200 UTC, the 0-3 and 0-6-km bulk shear magnitudes at KOAX were 10 and 20 m s^{-1}, respectively.

NOAA's Slater, IA profiler (Fig. 4) shows the change in wind shear structure that occurred between 12 and 18 UTC on 29 June 1998. During this time, the winds increased in magnitude in the 3000 to 5000 m layer increasing both the 0-3 km and 0-6-km shear magnitudes from 5 and 20 m s^{-1} to 20 and 35 m s^{-1}, respectively. By 18 UTC, the wind profile

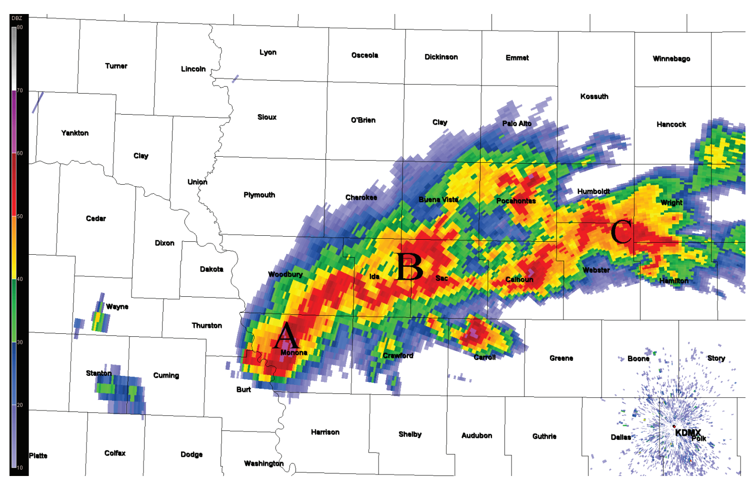

Fig. 8. 0.5 degree base reflectivity data from the KDMX radar at 1716 UTC 29 June 1998. Storms "A", "B" and "C" are identified. At this time, Storms A, B and C all contained persistent rotating cores, consistent observations of other supercells. For reference, KDMX is located in the lower right-hand corner in northeast Polk County. The dBZ scale is on the left. All radar data are plotted with the GRLevel2 software package from www.grlevelx.com.

is one that is generally supportive of both supercellular and linear convective modes.

The 1200 UTC 850-mb analysis on 29 June 1998 (Fig. 5) revealed a trough extending from Ontario into northern New Mexico as well as a low-level jet (LLJ) of 17 m s^{-1} that extended from the northern Texas Panhandle into central Kansas. The 850-mb temperature/dew point field (Fig. 6) showed a thermal ridge extending from the Desert Southwest into central Iowa and ample quantities of moisture present as evidenced by dew points exceeding 12°C from Texas into Nebraska and Iowa. At this time, strong warm air advection (WAA) at 850-mb (> 2.5 ^{o}C h^{-1}) was occurring in the region, extending from western Kansas to the Iowa/Illinois border. Additionally, 850-mb moisture convergence was strongest over Nebraska and eastern Iowa with values exceeding 0.5 g kg^{-1} h^{-1}. The strongest advection of θ_e was also identified over eastern Nebraska and western Iowa at 1200 UTC with values greater than 1.4 K h^{-1}. The locations of maximum values of moisture convergence and θ_e advection are consistent with those shown in Johns (1993) to be initial indicators of areas most favorable for initiation of convection.

At 500-mb (Fig. 7), moderate west-northwest flow and broad diffluence is observed over Iowa. Consistent with Johns (1993), the QLCS developed south of the 500-mb jet axis that is located over northern South Dakota.

4. Storm Scale Structure and Evolution

Examination of the system's overall reflectivity structure at 1716 UTC on 29 June 1998, revealed a cluster of organized deep convective storms stretching from 120 km northeast of KDMX to 80 km north of KOAX (Fig. 8). At this time, three discrete cells located to the west and northwest of KDMX were found to contain persistent rotating centers (Storms A, B, and C in Fig. 8). At this time, the convective system was associated with several severe hail and wind reports (NCDC 1998). In each of these storms, the mesocyclones (Andra 1997) originated at midlevels, similar to observations of other supercells as recorded by Burgess et al. (1982). The remainder of this paper will investigate one particularly intense portion of the convective system (Storm B) and its associated circulations as it approached KDMX from an initial range of 100 km.

At 1716 UTC, a reflectivity cross section, which was oriented normal to the leading edge of Storm B (not shown), revealed a nearly vertical convective tower extending to an altitude of approximately 15 km. This observation is consistent with those made by Rasmussen and Rutledge (1993; hereafter RR93) during the QLCS's intensifying stage, as well as Weisman's Stage II of bow echo development (tall echo stage; Weisman 1993). RR93 noted that during this

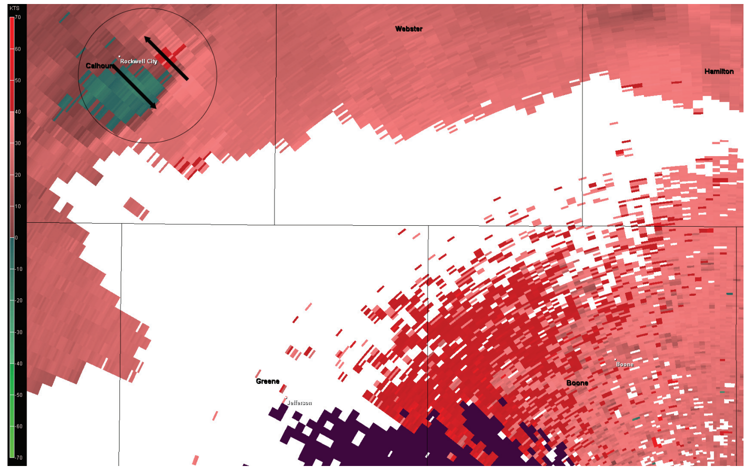

Fig. 9. Storm-relative velocity (SRV) radar data at 0.5 degrees from the KDMX radar at 1716 UTC 29 June 1998. Mesovortex 1 (C1) is circled. A storm motion of 295° at 35 kt (18.0 m s^{-1}) was used to compute the SRV. Arrows indicate the direction of motion toward or away from the radar. At this time, C1 is located approximately 100 km northwest of KDMX. The SRV scale is on the left.

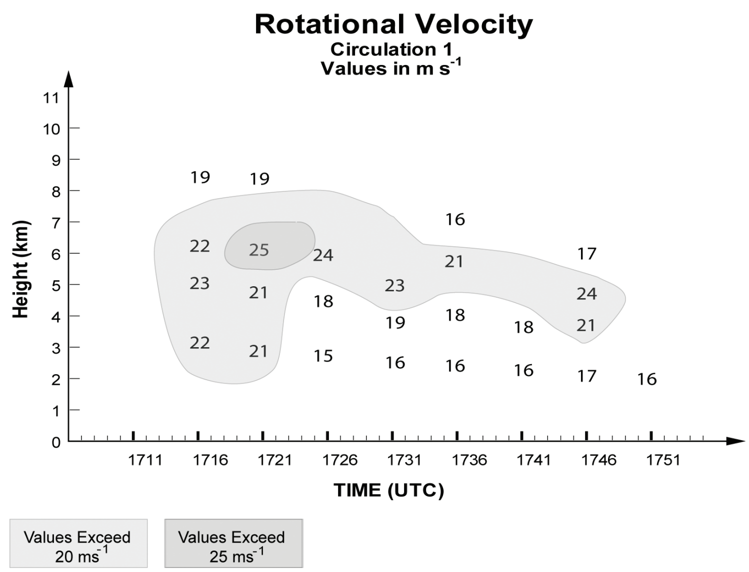

Fig. 10. V_r trace of C1 from 1716 - 1751 UTC 29 June 1998. Rotational velocities are shown in m s^{-1}. Prior to 1716 and after 1751 UTC, C1 was indistinguishable. Note how the maximum values of rotation are maintained, > 4 km AGL for much of the circulation's lifetime.

stage the cells at the leading edge grow to their greatest vertical extent and the convective updrafts attain their highest updraft speeds. Weisman (1993) found that during Stage II, strong, erect updrafts are produced because of the balance attained between the vorticity generated on the downshear side of the cold outflow and the vorticity generated by the ambient VWS.

The first storm-scale cyclonic circulation associated with

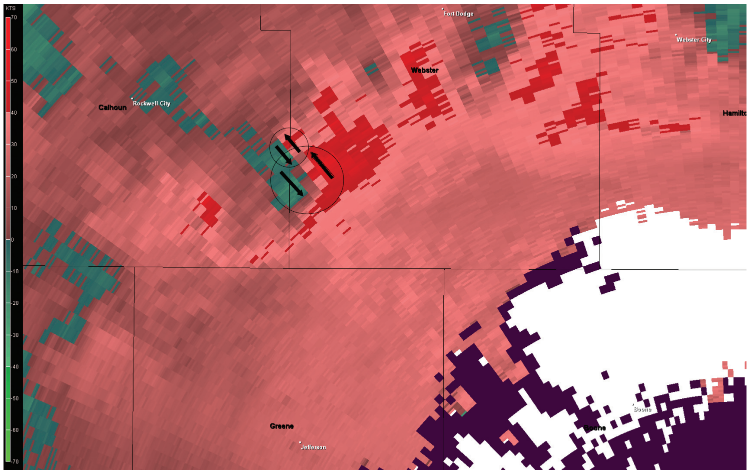

Fig. 11. 1.5 degree SRV radar data from the KDMX radar at 1736 UTC 29 June 1998. C1 is denoted by the small circle and C2 is marked by the larger circle. A storm motion of 295° at 35 kt (18.0 m s^{-1}) was used to compute the SRV. Arrows indicate the direction of motion toward and away from the radar. The SRV scale is on the left.

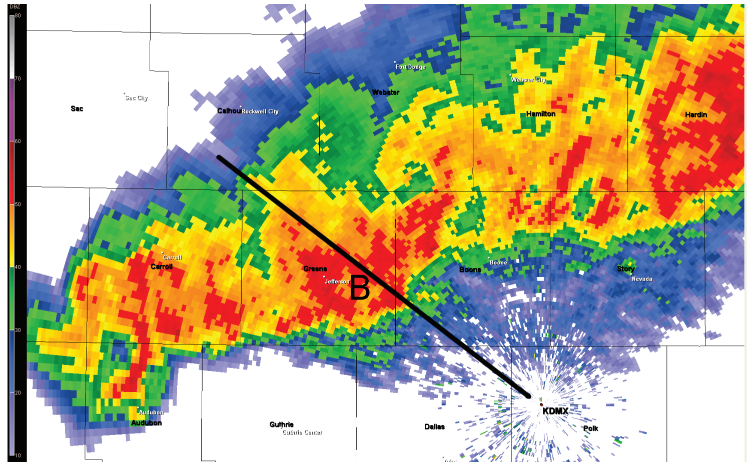

Fig. 13. 0.5 degree base reflectivity data from the KDMX radar at 1811 UTC 29 June 1998. The black line represents the location of the cross-sections through storm 'B" presented in Figs. 14 and 15. For reference, KDMX is located in northeast Polk County. The dBZ scale is on the left.

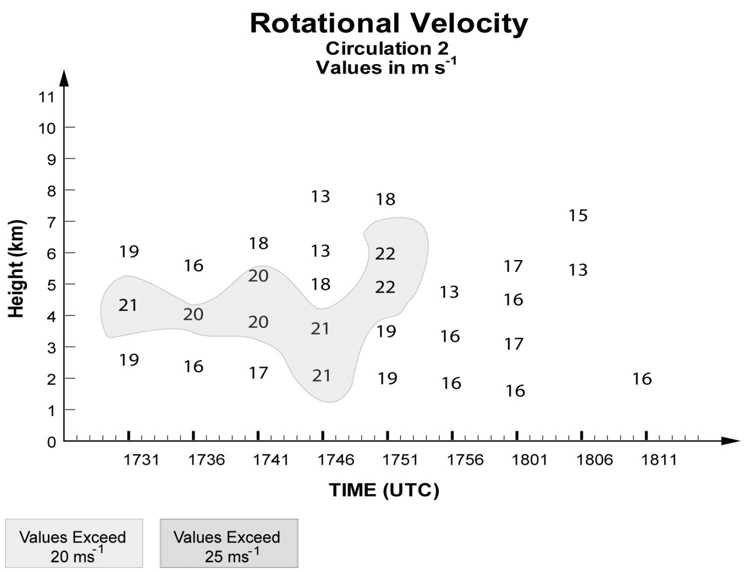

Fig. 12. V_r trace of C2 between 1731 and 1811 UTC 29 June 1998. Rotational velocities are shown in m s $^{-1}$. Prior to 1731 and after 1811 UTC, C2 was indistinguishable. Similar to C1, C2 generally maintained its strongest circulation > 4 km AGL.

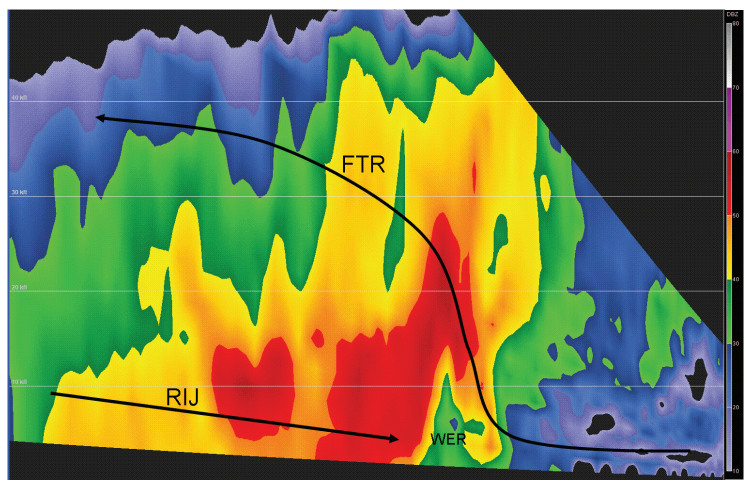

Fig. 14. Base reflectivity cross-section oriented normal to the leading edge of Storm "B" along the line shown in Fig. 13. Each horizontal line represents an increment of 10,000 ft (3.048 km). The horizontal dimension of the image is 35 nm (64.82 km). The arrows represent the approximate positions of the front-to-rear (FTR) and rear-to-front (RTF) flows within the system. The location of a weak echo region (WER) is also indicated in the figure. The dBZ scale is on the right.

Storm B (C1) was detected at 1716 UTC between 3.5 and 8 km above ground level (AGL) in southwestern Calhoun County (Fig. 9). At this time, C1's maximum rotational velocity (V_r) of 23 m s^{-1} was located approximately 5 km AGL (Fig. 10) and it maintained a consistent diameter of 5 km throughout its depth (not shown). At an initial range of 100 km, C1 immediately met the criteria for a strong mesocyclone (Andra 1997). These observations are consistent with Burgess et al. (1982) who showed that vortices associated with supercells originated at the storm's midlevels. C1 was initially detected near a weak echo region (WER) on the leading edge of Storm B. Between 1716 and 1737 UTC, C1 maintained a diameter of approximately 5 km as well as consistently stronger shear magnitudes between 5 and 7 km AGL. After 1741 UTC, the vortex became embedded near Storm B's high reflectivity core and weakened (see Fig 10). C1 became indistinguishable after 1751 UTC.

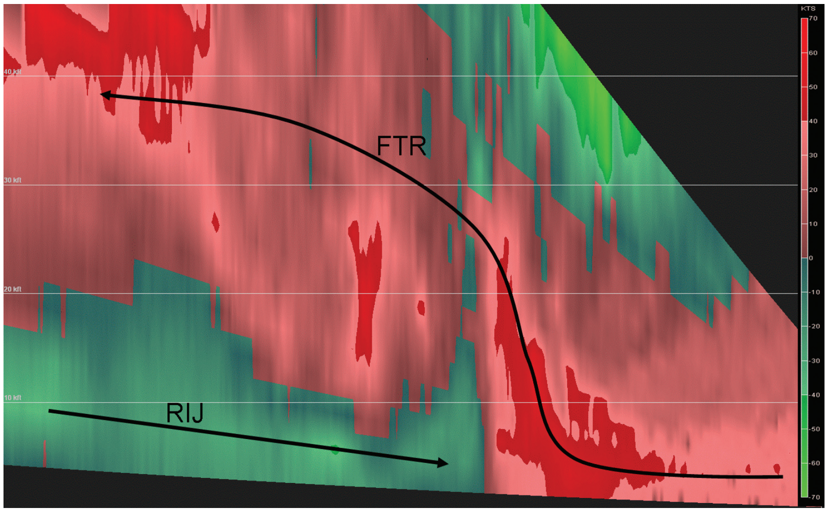

Fig 15. SRV cross-section oriented normal to the leading edge of Storm "B" along the line shown in Fig. 13. Each horizontal line represents an increment of 10,000 ft (3.048 km). The horizontal dimension of the image is 35 nm (64.82 km). The arrows represent the approximate positions of the front-to-rear (FTR) and rear-to-front (RTF) flows within the system. The SRV scale is on the right.

The second cyclonic vortex detected within Storm B (C2) was initially identified at 1731 UTC, 3 km south of the path of C1, on the border of Calhoun and Webster Counties (Fig. 11; shown at 1736). Consistent with observations of C1, C2 also revealed a mid-level origin with its strongest cyclonic shears (23 m s^{-1}) located near 5 km AGL. At this time, C2's depth was 3 km and its diameter was approximately 3.5 km. Between 1731 and 1746 UTC, C2 expanded to its greatest vertical depth of approximately 8 km and largest diameter of 6 km. C2 maintained its strongest shear magnitudes between 3.5 and 6 km AGL until 1756 UTC (see V_r trace in Fig. 12). Then, the cyclonic shear associated with C2 weakened considerably and became uniform throughout its decreasing depth. C2 appeared to take a similar trajectory to C1, gradually advecting rearward into Storm

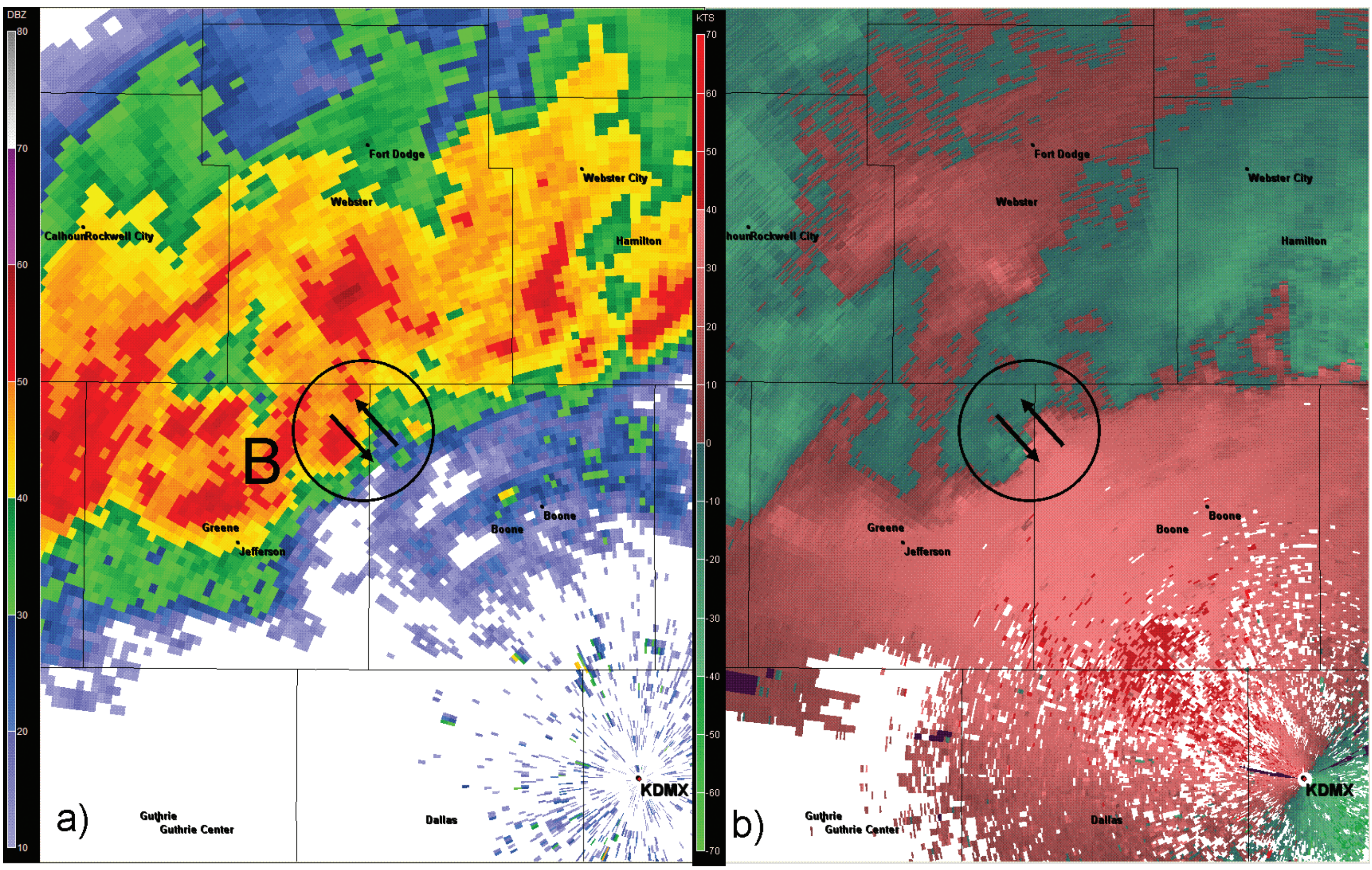

Fig. 16(a). 0.5 degree base reflectivity data from the KDMX radar at 1806 UTC 29 June 1998. Circle marks location of C5 associated with storm B while arrows indicate locations of the maximum inbound and outbound radial velocities, relative to the KDMX radar. At this time, data suggests that Storm B was developing an appendage in response to the existence of C5. **(b).** C5 is also shown in the 0.5 degree SRV data from KDMX radar valid at the same time. A storm motion of 295° at 35 kt (18.0 m s-^{1}) was used to compute the SRV.

B's high reflectivity core and weakening. Between 1716 and 1806, numerous severe straight-line winds were reported (NCDC 1998).

At 1811 UTC, radar data indicated that the MCS had solidified into a line that was nearly 200 km long and orientated east-northeast-west-southwest across west-central and central Iowa (Fig. 13). At this time, Storm B was located approximately 50-80 km northwest of KDMX. The reflectivity cross-section (orientated normal to Storm B's leading edge) taken at 1811 UTC revealed a WER along the HP storm's southeast flank associated with new cell development between 4 and 7 km AGL (Fig. 14).

At this time, the 50 dBZ core extended to a height of approximately 11 km (see Fig. 14). During this time, surface gusts associated with Storm B exceeded 35 m s^{-1} over southwest portions of Boone County Iowa, 50 km northwest of KDMX (NCDC 1998). The corresponding velocity cross-section (Fig. 15) showed a steep ascending branch of the front-to-rear flow (FTR), as well as the gradual descending rear inflow. These observations are similar to those shown in Atkins et al. (2005) and indicate that the QLCS has entered the beginning of its mature stage. However, the existence of a steep ascending branch of the FTR at this time is in contrast to the gradual ascending branch shown in the latter part of the mature stage (RR93) and Weisman's Stage III (Weisman 1993).

5. Examination of a Tornadic Mesocyclone at Close Ranges

BM98's examination of tornadic vortices associated with classic supercells that occurred in close proximity to a WSR-88D revealed a consistent pattern of vortex development prior to and during tornadogenesis. They noted that before tornado formation, Doppler radar indicated the existence of strong rotation well above the cloud base (assumed to be 750 m) and strong convergence below the cloud base. *Just before* tornado formation, there was strong rotation well above the cloud base to near cloud base as well as the presence of strong convergence near and below the cloud base. Finally, at the time of tornado formation, strong rotation was present through a deep column, including below the cloud base, with maximum rotation located at a height just above the cloud base.

At less than 30 km from the KDMX WSR-88D, the close proximity of mesovortex 5 (C5) allowed for a detailed examination of its vortex characteristics. C5 was initially detected along the leading edge of Storm B at 1806 UTC (Fig 16). At this time, C5 revealed an overall depth of 3

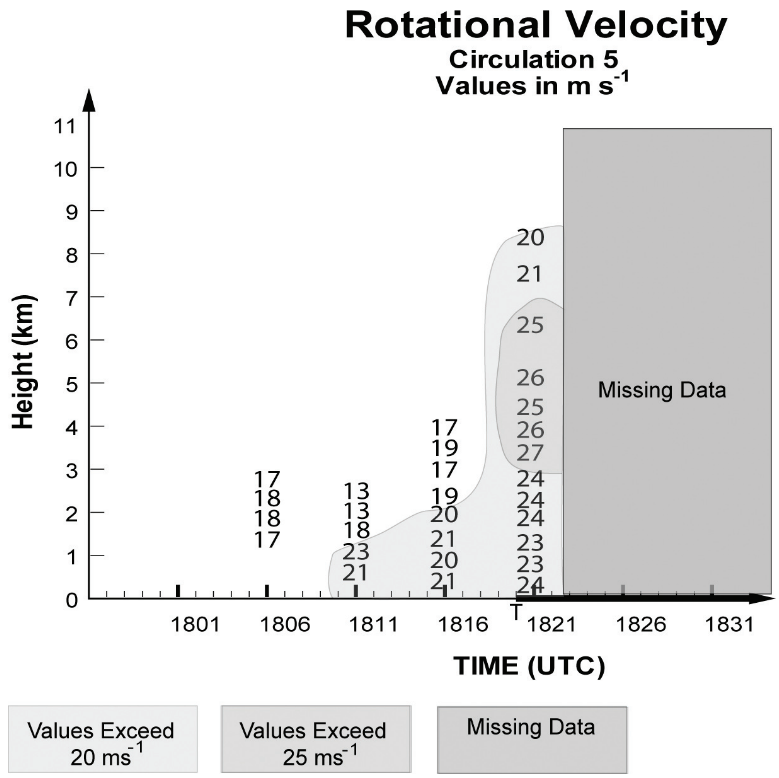

Fig. 17. V_r trace of C5 between 1806 and 1821 UTC on 29 June 1998. Rotational velocities are shown in m s^{-1}. The "T" on the abscissa represents the time of the first reported tornado touchdown. Prior to 1806 UTC, C5 was indistinguishable. Unlike C1 and C2, C5 developed at low-levels and maintained very strong rotation < 4 km AGL throughout this period.

km and a core diameter of 2.5 km. In contrast to observations of non-tornadic vortices C1 and C2, C5 originated in the lower-levels of Storm B and was completely contained within 4 km of the surface (see V_r trace in Fig 17). Between 1811 and 1821 UTC, C5 rapidly deepened and intensified. At 1821 UTC, the magnitude of the V_r associated with C5 exceeded 23 m s^{-1} between 200 m and 7 km AGL. The first report of a tornado associated with this mesocyclone occurred at approximately 1820 UTC southeast of Berkley, Iowa in southwest Boone County (NCDC 1998). Tornadogenesis occurred just prior to when C5 attained its greatest vertical depth (8 km) and strongest V_r values (25-28 m s^{-1}.) This is consistent with findings in other cases examined in the Mid-Mississippi Valley region (Przybylinski et al. 2000).

At 1821 UTC, one minute after tornado touchdown, C5 was located at a range of approximately 26 km from KDMX (Fig. 18a and 18c). At this time, C5 revealed a cyclonic-convergent velocity signature at the 0.5° elevation angle (0.4 km AGL; Fig. 18d) and a symmetrical vortex structure at the 1.5° elevation angle (1.0 km AGL) and above (Fig 18b). This observation differs slightly from those made by BM98, who observed a

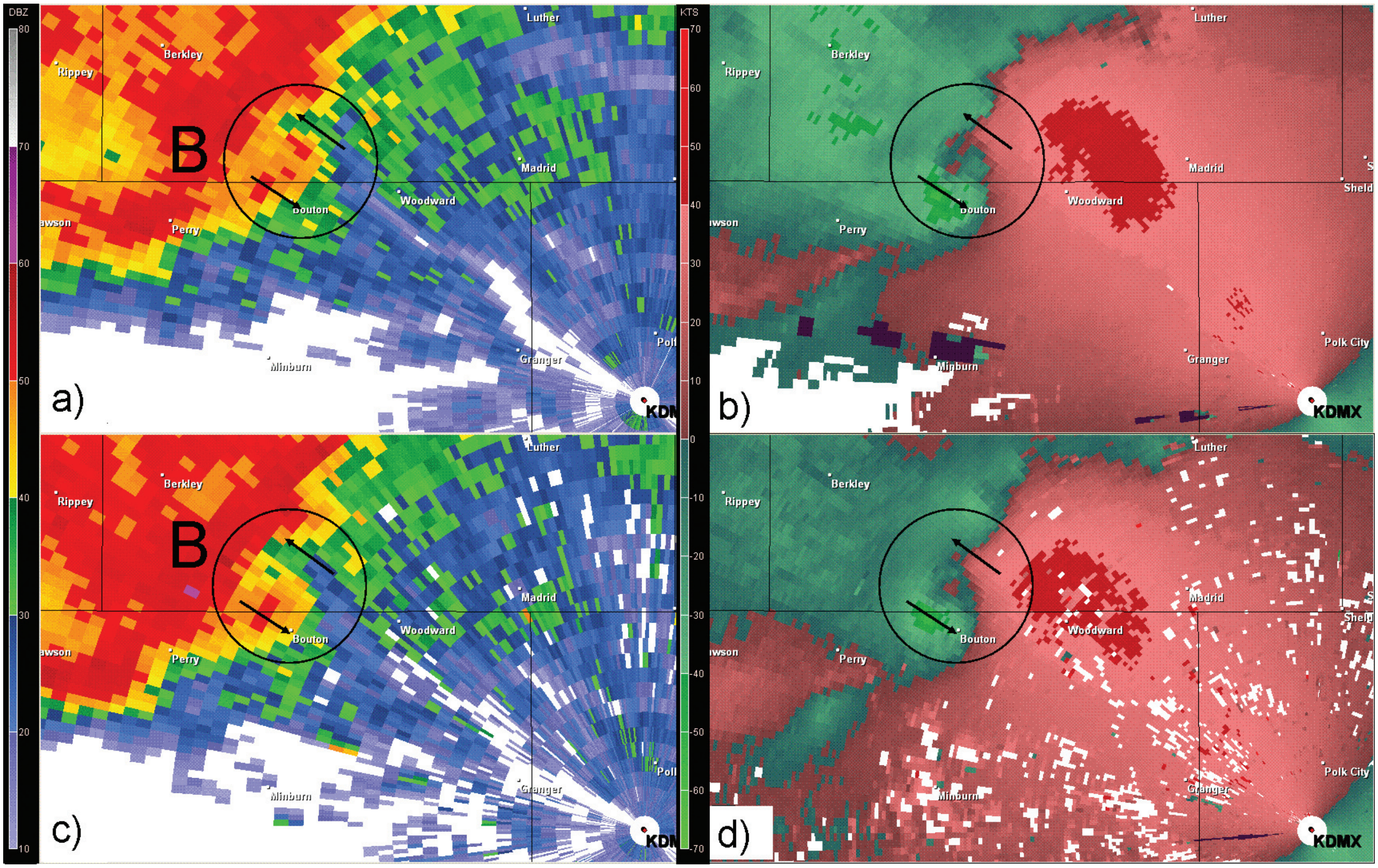

Fig. 18(a). 1.4 degree base reflectivity data from the KDMX radar at 1821 UTC on 29 June 1998. C5 is indicated by a circle while arrows mark the location of the maximum inbound and outbound radial velocities relative to the KDMX radar. The dBZ scale is to the left. Note the existence of the hook echo as a result of the presence of C5.

(b). 1.4 degree SRV data from the KDMX radar valid at the same time. Circle and arrows are as in Fig. 18a. A storm motion of 295**°** at 35 kt (18.0 m s^{-1}) was used to compute the SRV. The SRV scale is to the left.

(c). As in Fig. 18a except 0.5 degree base reflectivity is shown.

(d.) As in Fig. 18b except 0.5 degree SRV data is shown.

purely rotational signature at the lowest levels at the time of tornado formation. The observed convergent signature in this case is likely associated with the rapid advancement of the precipitation-loaded rear-flank-downdraft. Due to a power outage, the next volume scan recorded from KDMX did not occur until 1833 UTC, at which time the reflectivity structure showed a distinct hook echo as a result of the redistribution of precipitation due to the presence of C5 (Fig.19a and 19c). Additionally, the velocity structure at 1833 UTC showed a nearly symmetrical vortex at the lowest two elevation slices (0.5° and 1.5°; 0.1 km and 0.2 km AGL) and above (Fig. 19b and 19d). These observations agree with those recorded by BM98. However, it is interesting to note that strong convergence (ΔV of 58 m s^{-1}) was detected along the northern periphery of C5's core, 8 km northwest of KDMX. Subsequent elevation slices above the convergent velocity signature (i.e., above 1 km AGL) exhibited a cyclonic-convergent velocity couplet. The overall velocity pattern at this time is very complex and the loss of data and limited sampling resulted in obtaining only a partial understanding of the overall vortex structure of C5. However, the velocity structure at 1833 UTC (Fig. 19b and 19d) does suggest the possibility of a "double core" vortex structure.

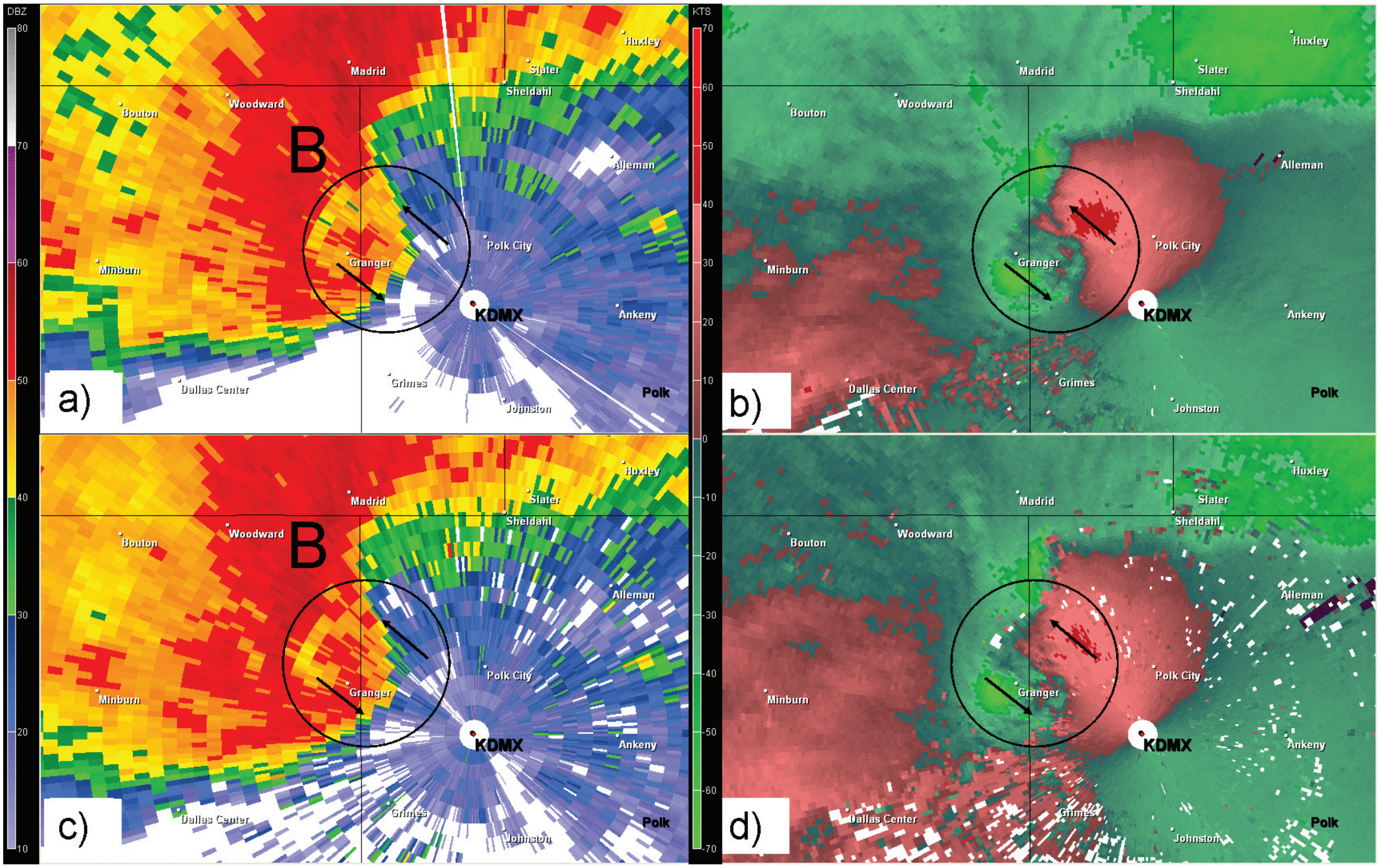

Fig. 19(a). 1.4 degree base reflectivity data from the KDMX radar at 1833 UTC on 29 June 1998. C5 is indicated by a circle while arrows mark the location of the maximum inbound and outbound radial velocities relative to the KDMX radar. The dBZ scale is to the left.

(b). 1.4 degree SRV data from the KDMX radar valid at the same time. Circle and arrows are as in Fig. 19a. A storm motion of 295° at 35 kt (18.0 m s^{-1}) was used to compute the SRV. The SRV scale is to the left.

(c). As in Fig. 19a except 0.5 degree base reflectivity is shown.

(d). As in Fig. 19b except 0.5 degree SRV data is shown.

6. Summary and Conclusions

During the late morning and early afternoon of 29 June 1998, a cluster of strong to severe thunderstorms formed over northeast Nebraska and moved southeastward into northwest Iowa. The cluster matured into a line of discrete storms from north-central to west-central Iowa, exhibiting high-precipitation supercell characteristics. The discrete storms gradually evolved into a QLCS across east central through central Iowa. Many of these storms were responsible for the production of damaging winds, hail, and tornadoes.

The 850-mb low-level jet, orientated from the Texas Panhandle into south-central Nebraska, transported high θ_e air northward into the region of severe storm development over northeast Nebraska. Similar to a warm season "progressive" derecho environment, the severe storms formed along a west-east frontal boundary which extended from east-central Nebraska through southeast Iowa and into central Illinois. Surface dew points of 23°C, pooled along and south of the surface boundary through southeast Nebraska and into southwest Iowa, resulted in a region of highly unstable air. Through mid day (1800 UTC), the surface boundary moved little across south-central and southeast Iowa. The southerly flow south of the boundary continued to transport warm, moist, unstable air north and northeastward, resulting in continued pooling of surface dew points along and to the south of this boundary.

The initial cluster of severe storms likely formed in a highly unstable, strongly sheared environment. Although the surface-based CAPE computed from the 1200 UTC Valley, NE (KOAX) sounding was 2493 J kg^{-1}, a modified sounding based on actual temperature and dew point values, resulted in CAPE exceeding 3500 J kg^{-1} over central Iowa at the time of convective initiation. A strong, deep-layer shear profile was evident by late morning from the Slater, Iowa profiler when magnitudes of the 0-6-km shear reached 30 m s^{-1}. In contrast, the 0-3-km shear from the Slater profiler was weak with a magnitude of 12 m s^{-1}. This is in contrast to observations recorded by Przybylinski et al. (2000) where 0-3 km shear values for bow echo events exceeded 17 m s^{-1}. The pre-convective thermodynamic and shear profiles suggested that the convective mode would be primarily supercellular.

During the early part of the storm development, the overall system reflectivity structure evolved from an area of broken cells into a solid line of convective storms from northeast to southwest Iowa. Several elements of this convective system exhibited HP supercell reflectivity structures with mid-level rotating centers (mesocyclones) located along the downshear flank of each of these storms. The overall storm reflectivity characteristics included strong *low-level* reflectivity gradients along the storm's downwind flank capped by high reflectivities aloft, suggesting the location of the storm's updraft region or WER. Reflectivity cross-sections taken normal to the leading convective cells within the line confirmed the existence of a WER.

Several storm-scale mesovortices associated with Storm B were identified during this period between 1700 and 1833 UTC, suggesting one variation of the HP supercell theme. Many of these rotating centers originated from mid-levels (4-6 km AGL) and met the criteria for a mesocyclone. Mid-level vortex origination is related to the growth of a perturbation low-pressure area aloft which induces an upward directed perturbation pressure-gradient force on the right flank of the storm. This process results from the shear profile represented by a clockwise turning hodograph (Bluestein 1993). Similar to observations by Burgess et al. (1982), storm-scale vortices (C1 and C2) sampled in this study expanded upward and downward from mid-levels during intensification. However, V_r traces showed that the strongest cyclonic shears associated with these circulations remained at mid-levels (4-6 km AGL) and did not intensify to low-levels. Damaging winds and hail were associated with many of these storms during this period.

The overall MCS gradually changed into a nearly solid convective line as it approached south-central Iowa and the Des Moines area. Cross-sections of reflectivity and storm-relative velocity data were taken normal to the line. They showed that the internal flow structure of the MCS progressed from the latter part of the intensifying stage to the mature stage of MCS development, as shown by RR93 and Smull and Houze (1987). Observations of a deep, ascending branch of FTR flow and a gradual descending mesoscale rear inflow were noted during the mature stage.

The reflectivity structure and development of C5, tracking within 30 km of KDMX, was examined in detail and compared to near-radar observations of tornadic development associated with classic supercell storms by BM98. C5 can be characterized as a non-descending mesocyclone where the vortex originated below 4 km, deepened, and intensified within the next 20 minutes to an overall height of 8 km. The strongest cyclonic shears were detected within the lowest 3 km during the first 15 minutes and between 3 and 6.5 km 20 minutes after initial detection. These observations are similar to those described by Trapp et al. (1999). Tornadogenesis occurred just prior to C5 reaching its greatest depth, similar to observations noted by Przybylinski et al. (2000). The 1806 and 1811 UTC radial velocity data at the 0.5° elevation (0.5 km AGL) showed a radial convergent pattern, while a nearly symmetrical velocity structure was noted at the 1.4° (1.3 km AGL) and higher elevation angles. These observations are similar to those made within classic supercells by BM98, where a strong radial convergent velocity pattern was present near or below cloud base and strong rotation was noted above cloud base. During the 1816 UTC volume scan and just after tornado occurrence, Doppler velocity observations of radial convergence at the lowest elevation angle and deep rotation throughout much of the circulation's depth differ slightly from those of BM98; the radial convergence at the lowest elevation angle likely originating as a result of the advancement of the precipitation-laden rear-flank-downdraft. Independent of convective mode, the observation of rapid increases in low-level convergence and upward growth of rotation that initiates at low-levels is a useful indicator that will allow warning forecasters to gain confidence in anticipating tornadic development and issuance of subsequent warnings.

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Ron W. Przybylinski has been the Science and Operations Officer at the NOAA/National Weather Service Weather Forecast Office (WFO) in St. Louis, Missouri since 1991. Prior to 1991, Ron served as forecaster and station scientist at the NWSFO in Indianapolis, Indiana. Much of his early work on the study of bow echo evolution evolved during his tenure at Indianapolis. He received his B.S and M.S. in meteorology from Saint Louis University in 1977 and 1981. In late 1980's, he served as a project leader on the Operational Test and Evaluation of the WSR-88D Doppler radar. He is currently a principle investigator on the severe straight-line winds component of the COMET Cooperative Project with Saint Louis University.

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