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A SYNOPTIC CLIMATOLOGY OF DERECHO PRODUCING MESOSCALE CONVECTIVE SYSTEMS IN THE NORTH-CENTRAL PLAINS

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ABSTRACT

Synoptic-scale environments favourable for producing derechos, or widespread convectively induced windstorms, in the North-Central Plains are examined with the goal of providing pattern-recognition/diagnosis techniques. Fifteen derechos were identified across the North-Central Plains region during 1986–1995. The synoptic environment at the initiation, mid-point and decay of each derecho was then evaluated using surface, upper-air and National Center for Atmospheric Research (NCAR)/National Center for Environmental Prediction (NCEP) reanalysis datasets.

Results suggest that the synoptic environment is critical in maintaining derecho producing mesoscale convective systems (DMCSs). The synoptic environment in place downstream of the MCS initiation region determines the movement and potential strength of the system. Circulation around surface low pressure increased the instability gradient and maximized leading edge convergence in the initiation region of nearly all events regardless of DMCS location or movement. Other commonalities in the environments of these events include the presence of a weak thermal boundary, high convective instability and a layer of dry low-to-mid-tropospheric air. Of the two corridors sampled, northeastward moving derechos tend to initiate east of synoptic-scale troughs, while southeastward moving derechos form on the northeast periphery of a synoptic-scale ridge. Other differences between these two DMCS events are also discussed. Copyright © 2000 Royal Meteorological Society.

KEY WORDS: derechos; Great Plains; synoptic climatology

1. INTRODUCTION

During the overnight and early morning hours of 30–31 May 1998, an intense organized cluster of thunderstorms known as a mesoscale convective system (MCS) raced across Minnesota, Wisconsin and Michigan. These storms produced a severe windstorm (derecho) as they moved through the region ahead of an approaching cold front (Figure 1). Widespread damage was reported throughout the region, with several confirmed wind gusts greater than 50 $m\,s^{-1}$. Newspaper headlines used a variety of words to describe this event: war zone, devastating, unbelievable, wicked wind, blown to bits, among others (*Storm Data*, May 1998). As the derecho raced across Lake Michigan and White Lake Channel in Muskegon County, it produced a seiche that sank a tug boat. As the derecho moved onshore, a storm surge swept through the channel into White Lake, reaching the top of the channel walls. The derecho MCS dissipated over Western Ontario after killing five people, injuring 211 and producing at least $280 million in damage (*Storm Data*, May 1998). By comparison, during July 1997, hurricane Bertha made landfall in North Carolina as a category 2 storm and dissipated in New England causing $270 million in damage (*Storm Data*, July 1997).

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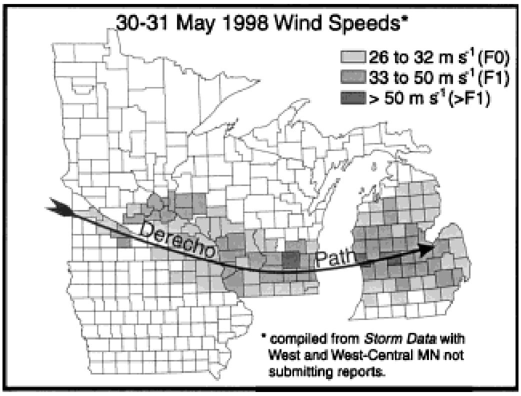

Figure 1. Counties containing severe convective wind reports associated with the 30–31 May 1998 derecho

Convectively induced windstorms have been referred to as derechos for more than 110 years (Hinrichs, 1888). Refinements to the definition of a derecho have evolved after numerous investigations of these systems (Howard *et al*., 1985; Johns and Hirt, 1987; Johns *et al*., 1990). A derecho includes any family of downburst clusters (winds >25 m s^{-1}) with temporal and spatial continuity and a major axis length of at least 400 km (Fujita and Wakimoto, 1981; Johns and Hirt, 1987). Derechos are produced by extratropical MCSs and occur throughout the Great Plains and eastern United States.

Investigations of derecho producing MCSs (hereafter DMCSs) have dealt with single events, mesoanalysis of the near and prestorm environments or numerical investigations into the governing dynamics of the parent MCS (Knupp and Cotton, 1985; Weisman, 1990, 1992; Schmidt, 1991; Klimowski, 1994; Bentley and Cooper, 1997; among others). Recently, a 10-year climatology of DMCSs has yielded insights into the temporal and spatial distribution of these events (Bentley and Mote, 1998). This study identified 11 activity corridors where derechos tended to group.

To date, regional climatologies examining environments conducive to the formation of long-lived, high wind producing MCSs have not been developed. A 4-year investigation of the characteristics of warm season DMCSs has proven to be quite useful in recognizing synoptic conditions favourable for their formation (Johns and Hirt, 1987). The following investigation is aimed at further delineating synoptic-scale environments favourable for producing derechos in the North-Central Plains. Another goal is to provide pattern-recognition/diagnosis techniques for identifying derecho conducive environments within activity corridors. After an initial examination of the DMCSs identified for this study, commonalities in the synoptic environments of these events will be examined.

2. STUDY AREA

The North-Central Plains include the following states: Iowa, Minnesota, Nebraska and North and South Dakota. A derecho event was included in this investigation if any portion of the associated severe convective wind (>25 m s^{-1}) swath, identified by *Storm Data*, crossed the defined study area.

3. DATA

Surface data used in this study were obtained from the National Weather Service (NWS) Automated Surface Observing System, the Aviation Weather Observing System and the Surface Aviation Observation network. These data were downloaded in Forecast Systems Laboratory (FSL) format from the National Climatic Data Center's (NCDC) on-line database. Hourly surface analyses were constructed using these datasets.

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Upper air data were obtained from the NWS rawinsonde network, with soundings taken at 00:00 h and 12:00 h UTC. These data were obtained from the CD-ROM *Radiosonde Data of North America* (1946–1993) published by NCDC (1994). Augmenting this dataset was the FSL's on-line database of rawinsonde observations for 1994 and 1995. In order for a sounding to be identified as representing the environment near the initiation of a DMCS, it must be within 250 km, and taken within 3 h of the first reported severe convective wind gust. The sounding also must not be 'contaminated' by ongoing convection. The same holds true for downstream soundings, with the additional criterion that they also must have been taken south of the DMCS track in the environmental inflow region ahead of the DMCS. Thermodynamic diagrams and composite hodographs were constructed using these datasets. Maps of pressure level data utilized the National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) reanalysis dataset. This joint effort has produced new atmospheric analyses using historical data in order to provide a more homogeneous dataset. The quality and utility of the reanalysis was superior to NCEP's original analyses due to the following:

(i) state of the art data assimilation methods were used;
(ii) more observations were used (i.e. marine surface, land surface, RAOBS, PIBAL, etc.); and
(iii) aircraft (military and commercial) observations augmented the standard observations (Kalnay *et al.*, 1996).

Temperature, specific humidity, u and v wind components and geopotential heights were obtained for the mandatory pressure levels. In addition, quasi-geostrophic omega values were obtained at 700 hPa. The dataset was ordered on-line through the National Oceanic and Atmospheric Administration (NOAA)/ Climate Diagnostic Center (CDC) and provided on 8 mm tapes in NetCDF format. The data were then converted to GEMPAK format for the analysis. For more information on the reanalysis dataset see Kalnay *et al.* (1996).

4. THE DISTRIBUTION OF DERECHOS

Derecho events used in the analysis were obtained from a derecho dataset compiled for the construction of a 10-year climatology over the period 1986–1995 (Bentley and Mote, 1998). Using a modified derecho identification approach adopted from Johns and Hirt (1987), the climatology consists of 112 derechos that occurred during all seasons throughout the central and eastern United States. During the 10-year period, 15 derechos formed over or passed through the North-Central Plains study area. These events occurred during the summer months with four events occurring in June, nine in July and two during August. The derecho events emanated from two activity corridors: southeastward moving northern tier (nine events) and northeastward moving Great Plains (six) (see Bentley and Mote, 1998 for a description of all corridors). Analysis of the DMCS environment took place at the temporal initiation, mid-point and decay periods of each event. The mid-point was determined by averaging the time between the first and last reported severe convective wind gust.

4.1. Southeastward moving northern tier events

Orientated parallel to the axis of northwest flow severe weather outbreaks, these events make up the predominant North-Central Plains derecho corridor (Figure 2). This was also the primary corridor of derecho activity during the Johns and Hirt (1987) investigation of warm season events. Northern tier events typically form in mid-summer with the majority (67%) developing in July (Table I). They appear to favour late evening or overnight development, with 56% of the DMCSs initiating between 21:00 h and 01:00 h UTC. Derechos making up the northern tier corridor are some of the longest tracking and lasting derechos in the United States (Table I). The overall average duration and path length of these events nearly equals the 16.5 h duration and 1400 km path length averages of an earlier investigation that focused on especially long-lived derechos (Johns *et al.*, 1990). The overall translation speed for northern

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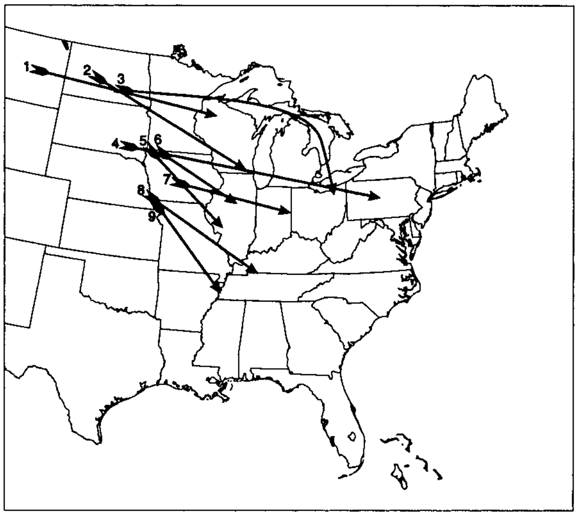

Figure 2. Southeastward moving northern tier derechos used in the analysis. Numbers correspond to events in Table I

Table I. Southeastward moving northern tier derechos occurring during the period 1986–1995

Event	Initiation date	Initiation time (h UTC)	Duration (h)	Path length (km)	Average speed (m s^{-1})	Tornado touchdowns
1	7/12/95	00:30	12.0	1034	24.0	0
2	7/27/95	00:50	18.6	1427	23.7	0
3	7/13/95	06:37	21.7	1823	24.1	0
4	7/7/91	13:25	16.6	1581	26.4	7
5	7/28/86	23:50	9.2	687	21.0	3
6	6/29/93	21:30	10.0	610	17.0	6
7	7/2/92	14:00	9.5	744	21.9	4
8	6/7/95	11:25	12.3	831	18.8	0
9	6/26/94	00:50	13.0	701	15.2	5
Average	—	—	13.7	1049	21.3	2.8

tier events of 21.3 m s^{-1} is consistent with previous investigations of warm season derechos (Johns and Hirt, 1987; Johns *et al.*, 1990). Another feature found with some DMCS events are tornadoes. Slightly more than half (56%) of northern tier events had associated tornado touchdowns, with one especially long-lived event containing seven reported tornadoes (Table I).

4.2. Northeastward moving Great Plains events

Northerly moving DMCSs comprise the second most active derecho corridor in the North-Central Plains (Figure 3). Roughly one-third of the events in this investigation are northeastward moving. Similar to northern tier systems, two-thirds of the derechos occurred in either June or July with half of the events initiating between 21:00 h and 01:00 h UTC (Table II). Northeastward moving events have a shorter duration and path length when compared with southeastward moving northern tier events. However, northeastward moving events can, at times, be significant tornado producers (Table II). Two northeastward moving events produced 48% of the reported tornado touchdowns for all DMCSs examined in this investigation. However, these were relatively weak, F0 and F1 tornadoes. Translation speeds for northeastward moving DMCSs also appear higher than the other two corridors with all events moving at speeds greater than 20 m s^{-1} (39 knots).

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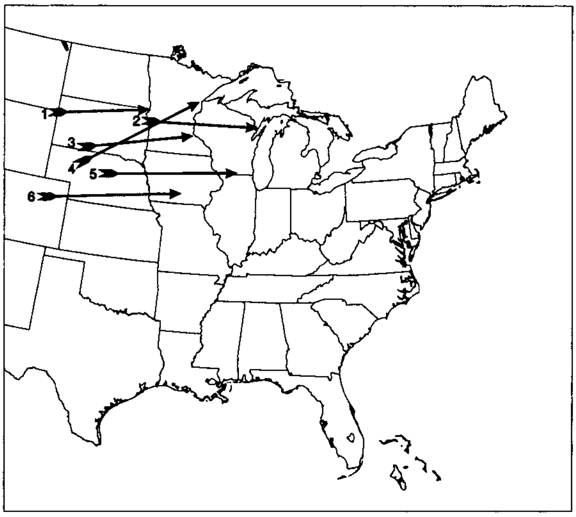

Figure 3. Northeastward moving Central Plains derechos used in the analysis. Numbers correspond to events in Table II

Table II. Northeastward moving Central Plains derechos occurring during the period 1986–1995

Event	Initiation date	Initiation time (h UTC)	Duration (h)	Path length (km)	Average speed (m s^{-1})	Tornado touchdowns
1	7/11/94	00:00	7.0	502	20.1	0
2	8/25/94	20:20	7.4	585	21.9	0
3	6/16/92	23:07	6.0	487	22.4	20
4	7/11/87	06:10	8.0	663	23.3	1
5	8/5/89	10:10	8.8	766	25.0	0
6	7/8/93	22:54	8.6	860	28.2	10
Average	—	—	7.6	644	23.5	5.2

4.3. Temporal distribution

A pattern evolves when examining North-Central Plains derechos by year and month (Table III). During the 10-year climatology, derechos emanated from only one activity corridor for each month. The primary derecho activity corridor changes according to adjustments in the location of favourable synoptic-scale forcing and regions of high convective instability. This underlies the importance of the synoptic environment in focusing the development and maintenance of MCSs in a particular location (Augustine and Caracena, 1994).

Table III. The monthly distribution of derechos by corridor for the period 1986–1995

Years	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
Months	6 7 8	6 7 8	6 7 8	6 7 8	6 7 8	6 7 8	6 7 8	6 7 8	6 7 8	6 7 8
SE moving northern tier	– 1 –	– – –	– – –	– – –	– – –	– 1 –	– 1 –	1 – –	1 – –	3 1 –
NE moving Central Plains	– – –	– 1 –	– – –	– – 1	– – –	– – –	1 – –	– 1 –	– 1 1	– – –

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5. THE SYNOPTIC ENVIRONMENT ASSOCIATED WITH NORTH-CENTRAL PLAINS DERECHOS

As illustrated when examining the temporal and spatial distribution of derechos occurring over a 10-year period, there are certain regions of the central and eastern United States where the synoptic-scale environment creates conditions favourable for DMCS formation (Bentley and Mote, 1998). A closer examination of one such region, the North-Central Plains, yields insights into the commonalities and differences that exist in DMCS development within each corridor. Models were developed to further elucidate commonalities in the synoptic environments of DMCSs emanating from each corridor. Similar to other investigations of synoptic conditions associated with severe convection, these models were developed by plotting the locations of synoptic features (e.g. the 850 hPa jet) for the initiation, mid-point and decay times of each DMCS and visually determining the mean position of these features for events in each corridor (Barnes and Newton, 1986; Johns *et al.*, 1990; Johns and Dorr, 1996). Characteristic patterns were then used to construct conceptual models.

5.1. Southeastward moving northern tier events

The synoptic environment in place during derecho events making up this corridor consists of a flow pattern similar to one that produces northwest flow severe weather outbreaks (Johns, 1984). It is also similar to an idealized synoptic-scale pattern favourable for warm season derechos identified in other investigations (Johns and Doswell, 1992; Johns, 1993). A detailed examination of this environment follows.

5.1.1. Initiation. Several common features among derecho events were identified in the surface analyses (Figure 4). The most striking was the orientation of surface features and the gradient of equivalent potential temperature (θ_e) present where the first convective wind gusts (>26 m s^{-1}) were reported (Figure 4). θ_e represents the adiabatic reduction to 1000 hPa of the sum of the actual air temperature and the temperature increment corresponding to the heat latent in water vapour. A large gradient of θ_e is indicative of regions where there is an influx of convectively unstable air and mass convergence of the

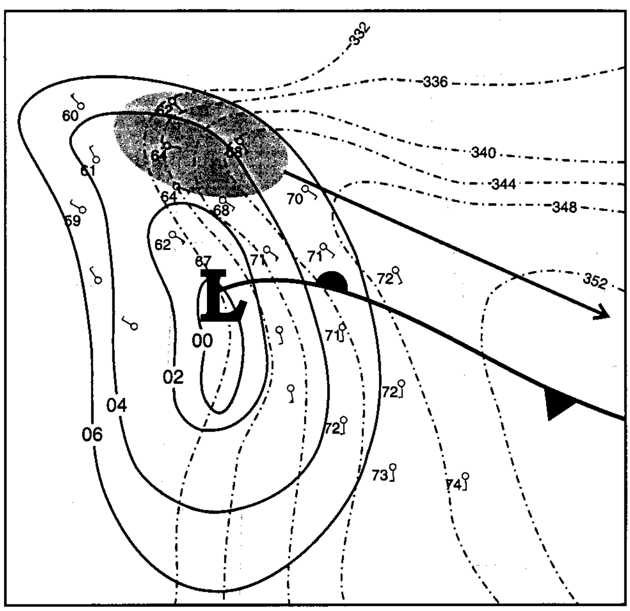

Figure 4. Idealized model of surface features associated with seven southeastward moving northern tier derechos. Shaded area represents the initiation region with arrow identifying the DMCS track. Dot-dashed lines are contours of θ_e while plotted values are dew point temperature (°F). Background map is provided for scale purposes only

wind field. All events initiated along a θ_e gradient (Figure 4). This demonstrates the significance of thermodynamic instability combined with mass convergence in promoting convective initiation. The average θ_e in the initiation region was 338 K. However, much higher values were found along the paths of the DMCSs. Nearly 86% of the DMCSs initiated north of an area of weak low pressure and thermal boundary. The circulation around the low provided a low level inflow, which maximized thermodynamic instability by transporting warm, moist air into the initiation region. Dew point temperatures in the initiation region were, on average, 19°C, although dewpoints of 20–25°C were found along and south of the weak thermal boundary. The environments where the DMCSs initiated compared favourably with environmental conditions found in previous investigations of derechos (Johns and Hirt, 1987; Johns *et al.*, 1990). However, contrary to previous findings, circulation around weak low pressure along the thermal boundary appeared essential in producing the surface convergence, θ_e gradient and wind field necessary for convective initiation and in maximizing gust front convergence.

Nearly two-thirds of the events initiated along or just east of an 850–700 hPa trough axis. This orientation produced a warm air advection (WAA) maximum downstream of the genesis region along the DMCS track. Only one-third of DMCS events initiated under 850–700 hPa WAA. Nearly 80% of the events initiated along an 850 hPa θ_e ridge axis, near the top of a 700 hPa thermal ridge. In environments where vertical differential vorticity advection is weak, evidence suggests low level WAA can produce enough forcing to initiate convection (Johns and Doswell, 1992). Two-thirds of the events developed in an environment producing synoptic-scale quasi-geostrophic lift. The average 700 hPa omega value for these events was $-16\ \mu b\ s^{-1}$. Thermal and moisture characteristics of the initiation region were also relatively high, indicative of the low level instability present (Table IV).

The mid-level environment was characterized by a weak shortwave trough found just west of the initiation region in all events. Two-thirds of the events formed west of a mid-level ridge axis, then moved over the ridge into northwest flow (Figure 5). This pattern resembles other synoptic-scale warm season derecho situations (Johns and Hirt, 1987; Johns and Doswell, 1992).

Two-thirds of the events also initiated under the upper-level divergence quadrant of a jet streak. While not a primary ingredient for derecho initiation, jet streaks can produce a more favourable environment for severe convection and DMCSs (Abeling, 1990; Schmidt *et al.*, 1990; Stensrud and Fritsch, 1994). The DMCSs that initiated proximal to a jet streak continued this orientation until moving under the ridge and dissipating. More than half the events dissipated in a region where 250 hPa flow decreased to less than 30 $m\ s^{-1}$.

The thermodynamic environment associated with derechos contains a high degree of convective instability and moderate to strong low-level vertical wind shear (Johns and Hirt, 1987; Przybylinski, 1995). Atmospheric soundings were obtained in order to assess the environment at initiation and downstream of North-Central Plains DMCSs. As shown by examining convective available potential energy (CAPE) and the lifted index (LI), the downstream environment was typically more unstable than at initiation (Table V). CAPE was calculated by lifting the lowest 500 m layer. The LI is the difference between the environmental temperature and the estimated updraft temperature at 500 hPa. The lower the

Table IV. Meteorological parameters associated with nine southeastward moving northern tier derechos[a]

	Temperature (°C)		Dew point temperature (°C)		Wind direction (°)		Wind speed ($m\ s^{-1}$)	
hPa	Initiation	Near mid-point	Initiation	Near mid-point	Initiation	Near mid-point	Initiation	Near mid-point
850	22:26	20:24	8:12	12:16	223	223	6:10	6:11
700	11:15	9:13	−1:−3	0:−2	252	270	11:15	11:15
500	−7:−11	−6:−10	−17:−19	−22:−26	253	277	17:19	16:20
250	−42:−47	−42:−46	—	—	262	286	26:30	27:31

[a] Values separated by a colon represent the range of values identified from events.

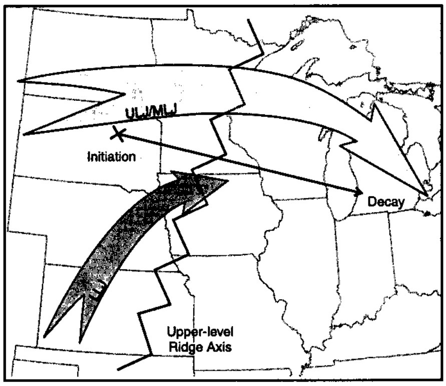

Figure 5. Idealized model of a mid-latitude synoptic-scale situation favourable for southeastward moving northern tier derechos. Background map is provided for scale purposes only

Table V. Thermodynamic parameters associated with southeastward moving northern tier derechos[a]

Time	CAPE (J kg^{-1})	Lifted index (°C)
Initiation	3437	−3.0
Near mid-point	3620	−8.4

[a] Five soundings were used to sample the initiation environment and seven soundings for sampling the downstream environment.

LI, the greater the convective instability. Composite hodographs were also constructed from the representative soundings (Figure 6). One interesting aspect of the hodographs was that the mid-level directional shear increased downstream. This was necessary for the DMCS to travel southeastward since the overall winds at the initiation region do not have a northwesterly component (Figure 6(a)). Moderate 800–3000 m shear characterized both hodographs, and given a southeasterly surface wind of 5 m s^{-1}, 0–3 km shear values would approach the strong threshold (> 18 m s^{-1}; Weisman, 1993). The differences in the two hodographs also indicate that the southeastward motion of the DMCS does not occur until the system travels out of the initiation region. Once organized, the DMCS cold pool increases leading edge convergence. This promotes convection along the leading edge of the gust front and allows for a storm propagation parallel to the prevailing wind, which turn northwesterly downstream. A significant portion of the downstream shear was orientated parallel to the wind damage swath. This makes it perpendicular to the main squall line. Typically, DMCSs that produce strong cold pools require a greater magnitude of vertical wind shear to produce a stronger and longer-lived system (Weisman, 1993). The northwesterly flow prevalent in the downstream hodograph combined with southeasterly surface winds and increased low-level directional shear.

Vertical cross-sections of θ_e and winds were also constructed parallel to the swath of severe convective winds (Figure 7). Veering winds with height were found along the entire track for all events. Nearly 80% of the DMCSs had the greatest vertical θ_e gradient occurring downstream of the initiation region (Figure 7). Over half of events had a low-level vertical decrease in θ_e of over 20 K near the spatial mid-point. This type of vertical θ_e gradient was found to be an important precursor to wet microburst development and in enhancing downdraft strength in MCSs (Atkins and Wakimoto, 1991; Przybylinski *et al.*, 1996). This illustrates that the vertical θ_e gradient is also important for DMCS development and maintenance.

5.1.2. Mid-point. The environment at the temporal mid-point of the DMCSs was similar to the initiation regions. Eight out of nine of the events continued to travel just north of a weak (1000–1004 hPa) surface low pressure centre. One event travelled south of a low pressure centre ahead of a cold front.

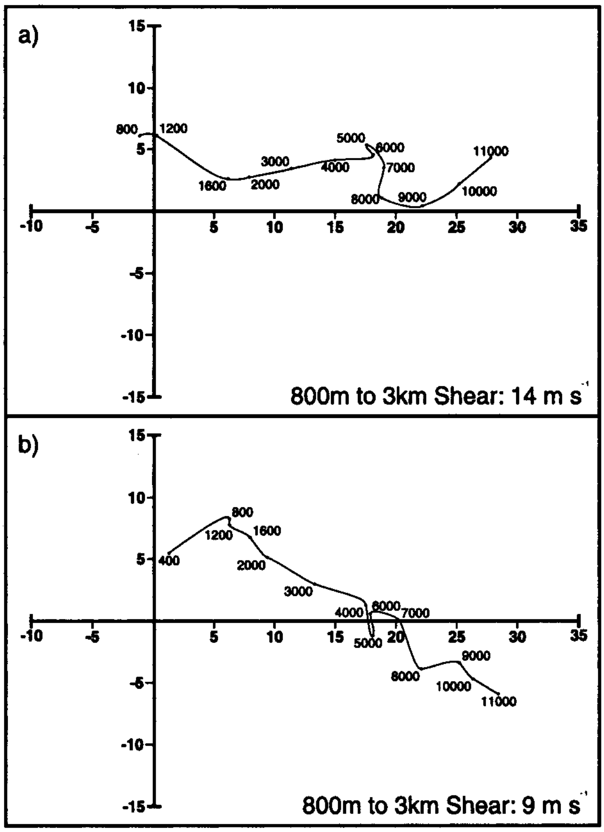

Figure 6. (a) Composite hodograph constructed from five soundings used to sample the initiation environment of southeastward moving northern tier derechos. (b) Composite hodograph constructed from seven soundings used to sample the downstream environment of southeastward moving northern tier derechos

The thermal boundary was very diffuse at this point as the DMCSs began to affect the synoptic environment with strong leading edge convergence produced by the convective-scale downdrafts and cold pool/mesohigh formation. The average maximum θ_e upstream of the DMCS at the temporal mid-point was 351 K and was the most convectively unstable air found along the path. Evidence suggests that the greatest instability is found at the mid-point of a derecho event (Johns and Hirt, 1987; Johns *et al.*, 1990). In order to produce this unstable environment, southeasterly winds of 5–10 m s^{-1} were occurring along the DMCS paths. Southeasterly winds were opposite in direction to the winds produced by the convective-scale downdrafts, which maximized leading edge convergence. This demonstrates the importance of high convective instability and low-level mass convergence in maintaining the quasi-steady state between the DMCS and synoptic-scale environment.

WAA was occurring along and ahead of over two-thirds of the DMCSs at 850 and 700 hPa. The systems also continued to travel just east of a low-level trough axis. This axis was especially visible at 700 hPa, where the DMCSs were located in the WAA region of a WAA/cold air advection (CAA) couplet produced by circulation associated with the low-level trough (Figure 8). All but one DMCS was then coincident with synoptic-scale quasi-geostrophic lift. Nearly 70% of the DMCSs travelled through an 850 hPa θ_e maximum found near the spatial mid-point, with the average along track θ_e approaching 342 K. This illustrates that low-level instability increases in magnitude and depth near the mid-point of the DMCS and appears essential for continued propagation. Another useful analysis tool is the 850 hPa moisture transport vector field. Moisture transport is calculated by taking the scalar multiple of the wind vector by the mixing ratio. The magnitude of this vector can then be plotted to show regions of high or low moisture inflow. A high magnitude of the moisture transport vector can be used to locate where the

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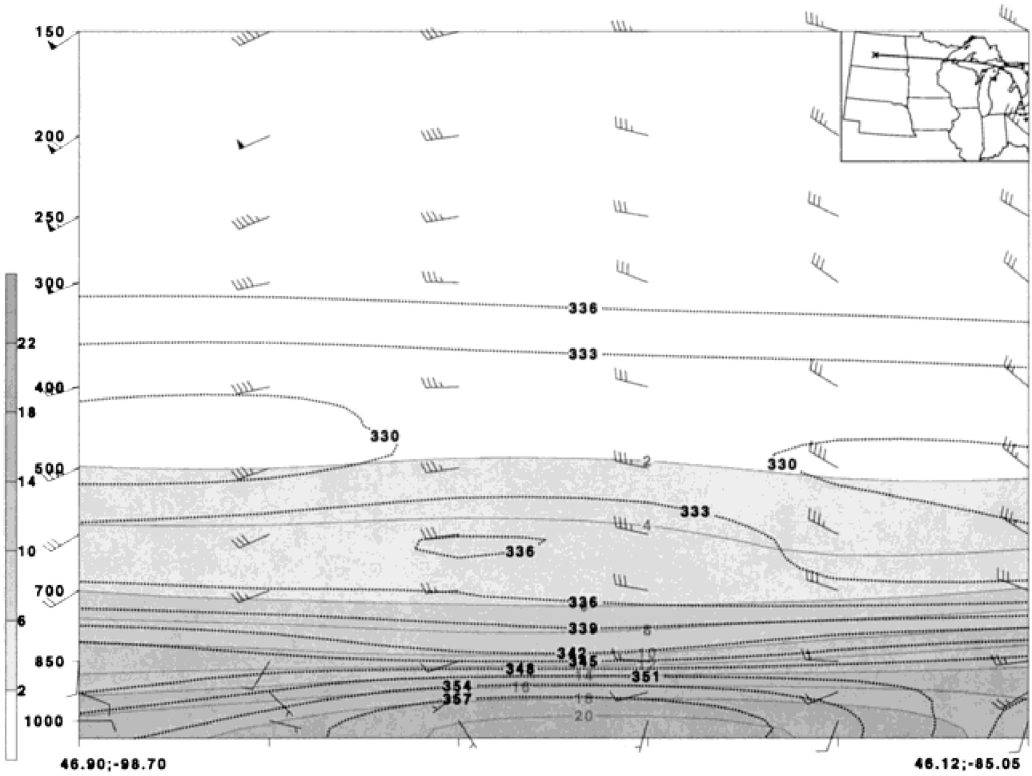

Figure 7. Vertical cross section of θ_e (K, dotted), mixing ratio (g kg^{-1}, shaded) and winds (knots) for 06:00 h UTC 13 July 1995 (initiation). Derecho track and location for vertical cross-section illustrated with solid arrow

low-level jet and moisture axis coincide. All but two DMCSs had moisture transport magnitudes greater than 50 g kg^{-1} m s^{-1} occurring over the entire track, with a maximum near the spatial mid-point just ahead of the system (Figure 9). High moisture inflow increases the CAPE and latent heat released in the updraft of the DMCS. This strengthens the cold pool and convective-scale downdrafts. Thermal and moisture characteristics of the mid-point environment were similar to the July averages presented in previous investigations (Table IV; Johns and Hirt, 1987).

At the temporal mid-point, nearly 80% of the DMCSs were travelling ahead of a 500 hPa shortwave trough. Although the trough was weak, over half of the events were near the 'nose' of a 23–28 m s^{-1} (45–50 knots) speed maximum. Two-thirds of the events formed west of a mid-level ridge axis, then moved over the ridge into northwest flow (Figure 5). This pattern resembles other synoptic-scale warm season derecho situations (Johns and Hirt, 1987; Johns and Doswell, 1992). In the majority of the events, the flow pattern paralleled the DMCS track and was moderately strong (18–21 m s^{-1}) for late spring and summer (Johns and Hirt, 1987). The average 500 hPa temperature was typical of those associated with summer tornado and northwest flow severe weather outbreaks (Johns, 1984; Table IV).

All events travelled slightly to the right (200–400) of the 700–500 hPa layer averaged winds initially, then gradually changed to move parallel to them in time. Compensating for this initial rightward turn, 700–500 hPa layer winds are a good predictor of DMCS movement. However, on average, the DMCSs moved 30% faster than the layer averaged wind speed and under conditions with lower wind speeds (<15 m s^{-1}), the DMCSs travelled 45% faster. At the temporal mid-point, two-thirds of DMCSs were located just to the west of a near surface θ_e maximum that gradually decreased toward the decay region. The vertical θ_e gradient also began to weaken downstream near the decay region as surface θ_e values decreased. As the θ_e lowered, convective instability also decreased and the cold pool weakened.

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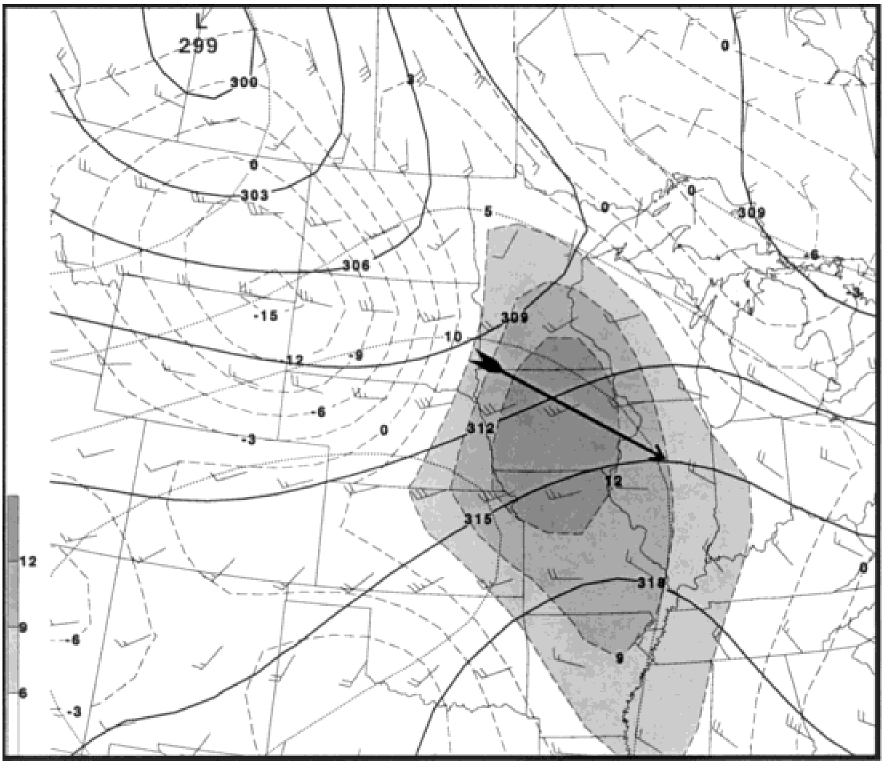

Figure 8. 700 hPa heights, winds ($m\,s^{-1}$), isotherms (°C, dotted), and thermal advection ($\times 10^{-1}$ °C h^{-1}, dashed lines and shading) for 00:00 h UTC 30 June 1993 (mid-point)

5.1.3. Decay. Several changes occurred near the decay region of DMCS events. The decay region is defined as the location where the last severe convective wind gusts are reported. In all events, the surface winds were southwesterly while the system continued to move southeasterly (Figure 10). This decreased leading edge convergence and the southwesterly flow transported drier low-level air ahead of the system. In 80% of the events, the along-track horizontal θ_e gradient weakened in the decay region. The average θ_e found in this region was 342 K. In all but one event, the surface low tracked well to the southeast of the DMCSs (Figure 10). This was likely the main reason why the winds backed to the southwest along the DMCS track.

As the DMCSs travelled east of the low-level trough axis, several environmental changes occurred. Although 850 hPa WAA was found over the decay region of all events, only half of the events had WAA occurring at 700 hPa. Thus, the depth of WAA decreased as the DMCSs travelled southeastward. This was likely due to the DMCSs moving into a ridge, thus weakening the overall flow. At 850 hPa, all events decayed on the east side of a θ_e ridge (Figure 11). In three-quarters of the events, the horizontal θ_e gradient weakened as the DMCS travelled eastward. The maximum magnitude of the moisture transport vector field was also found west of the decay region in three-quarters of the events. The decrease in depth and strength of these parameters illustrated that the DMCSs moved into a more stable environment.

Overall flow, as seen in the cross-sections, decreased as the DMCSs moved into a prevailing ridge. The cross-section of temperature advection near DMCS initiation, indicated 1000–700 hPa WAA occurring downstream in all but one event. The WAA ranged from 0.9 to 1.2°C h^{-1}. Three-quarters of the events also had CAA occurring above 500 hPa. Near the mid-point, all but one event had low-level WAA occurring. However, near the region of DMCS decay, the WAA maximum weakened and became much smaller.

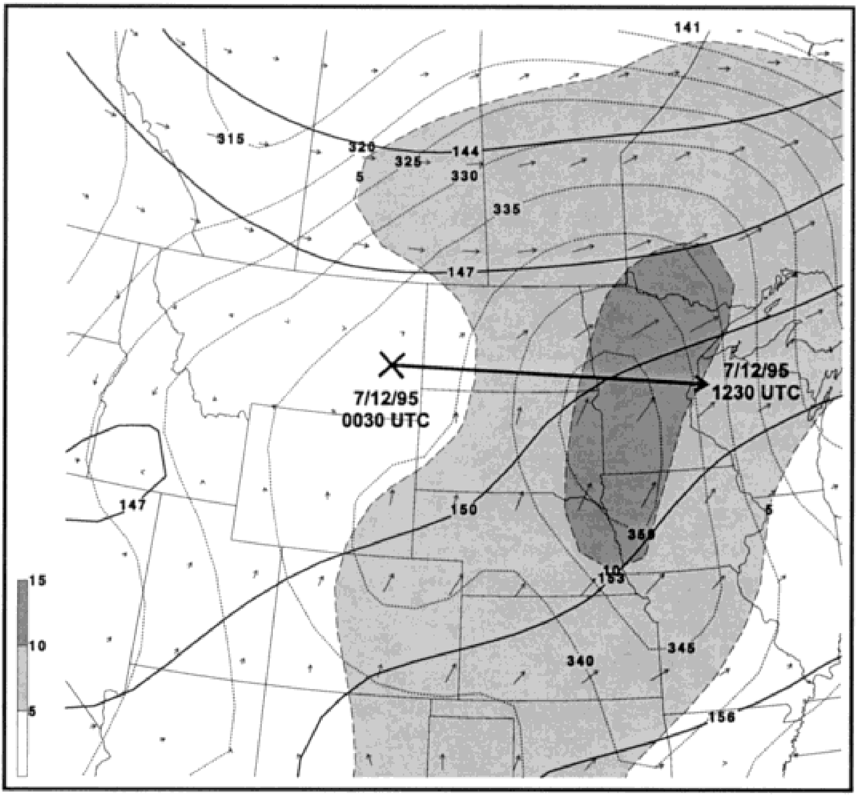

Figure 9. 850 hPa moisture transport (vectors and magnitudes, $\times 10^1$ g kg^{-1} m s^{-1}, dashed lines and shading), heights (dm) and θ_e (K, dotted lines) for 06:00 h UTC 12 July 1995 (initiation). Black line indicates the derecho track

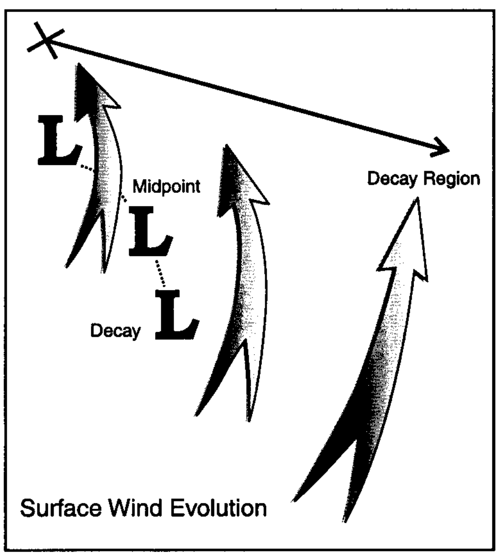

Figure 10. Conceptual diagram of the position of surface low pressure, winds and the southeastward moving northern tier derecho

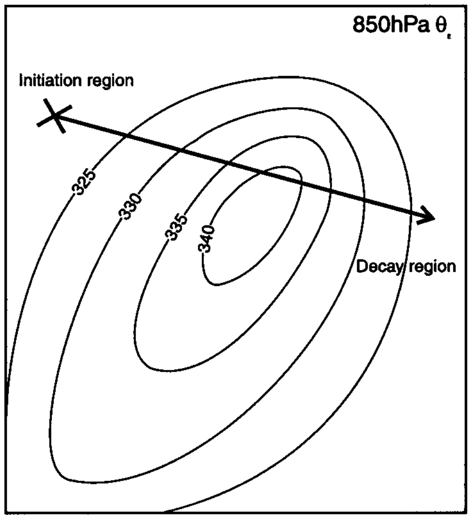

Figure 11. Conceptual diagram of the orientation of an 850 hPa θ_e ridge to the track of southeastward moving northern tier derechos

5.2. Northeastward moving Great Plains events

Similarities and differences were found in the synoptic environments producing northeastward moving Great Plains derechos when compared with southeastward moving northern tier events. In order for the environment to produce a northeastward moving DMCS, a trough axis west of the initiation region must be deep enough to produce southwesterly flow along the DMCS track. Specific features of this environment follow.

5.2.1. Initiation. The surface analysis constructed from examining environments producing northeastward moving derechos illustrates several similarities with southeastward moving northern tier events (Figure 12). Caution should be used, however, since only four events could be used to construct the surface analysis. Analysis of the low-, mid- and upper-levels utilized all six events. One striking similarity with southeastward moving events was the location of the DMCS initiation region with respect to a weak surface low pressure centre (Figure 12). Three of the four events sampled initiated north of surface low pressure over a θ_e gradient produced by cyclonic circulation. The thermal boundary present in northeastward moving events was orientated east to west, coincident with the moisture axis. The initiation region and track of the DMCS were consistent with northern tier southeastward moving events, travelling nearly parallel to the thermal boundary and moisture axis near initiation. Convective instability was slightly less than for southeast moving northern tier events with an average dew point temperature at the initiation region of 18°C and surface θ_e of 332 K. East to southeast surface winds prevailed near the DMCS initiation region, maximizing leading edge convergence.

Over 80% of the DMCSs formed in southwesterly flow found at 850 hPa. The approaching mid-level shortwave trough assisted in the production of a southerly low-level jet (Figure 13). Although weak northwesterly flow was occurring at 700 hPa, southwesterly flow was the predominant direction found at all other levels (Table VI). Two-thirds of the events had WAA occurring downstream, while only one event initiated under WAA. The average θ_e at 850 hPa was 338 K, 6 K higher than the average surface θ_e in the initiation region. This illustrates the very warm, moist environment found just above the surface during northeastward moving events (Table VI). Numerical simulations of a northeast moving DMCS illustrated a case where elevated instability played a role in system maintenance without the presence of a strong cold pool (Bernardet and Cotton, 1998). Although surface based instability was less than that found with southeastward moving northern tier events, low-level instability (i.e. 850–700 hPa) was quite similar. Over the initiation region, four of six events contained an along-track 850 hPa θ_e maximum and

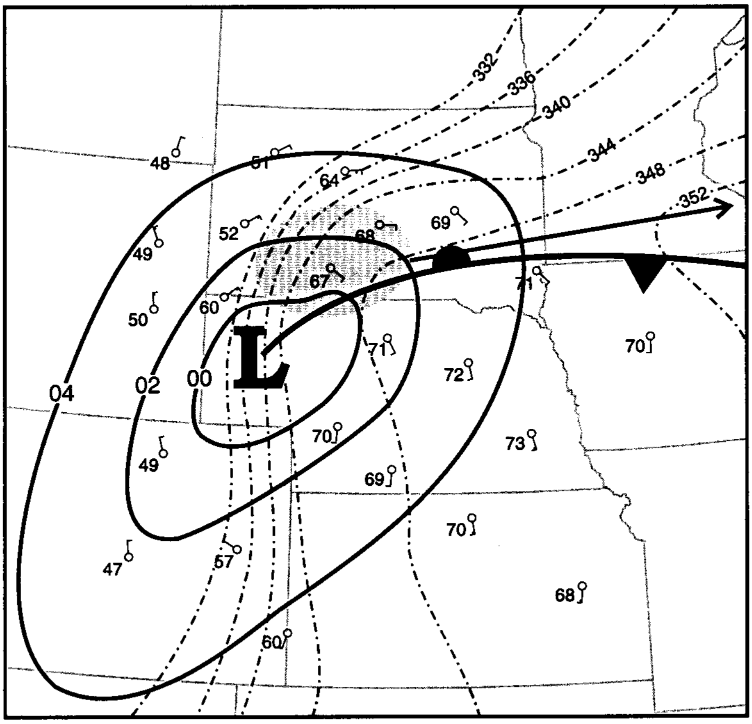

Figure 12. Idealized model of surface features associated with four northeastward moving Central Plains derechos. Shaded area represents the initiation region with arrow identifying the DMCS track. Dot-dashed lines are contours of θ_e while plotted values are dew point temperature. Background map is provided for scale purposes

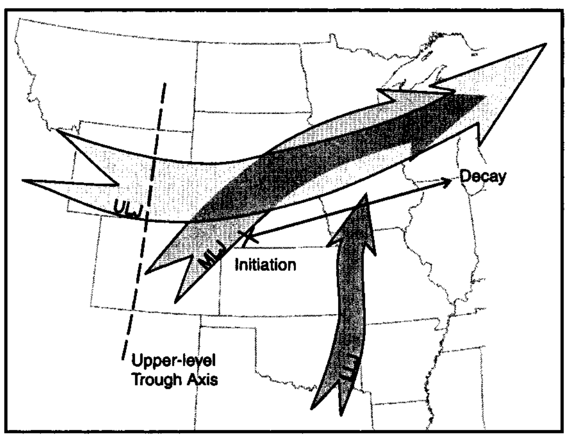

Figure 13. Idealized model of a mid-latitude synoptic-scale situation favourable for northeastward moving Central Plains derechos. MLJ is mid-level jet; ULJ is upper-level jet. Background map is provided for scale purposes only

a moisture transport maximum. Two-thirds of the DMCSs also formed slightly west of a thermal ridge axis at 700 hPa. Previous investigations have found this region to be an area of favoured DMCS development (Duke and Rogash, 1992). All but one event also formed in an area of synoptic-scale quasi-geostrophic lift signified by a 700 hPa average vertical velocity of $-16\ \mu b\ s^{-1}$.

In two-thirds of the DMCS events, the trough found west of the initiation region was evident through 500 hPa (Figure 13). These events also had west to southwest flow occurring along the entire track. Overall, the average 500 hPa temperature was slightly lower than for northern tier southeastward moving events (Table VI).

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Table VI. Meteorological parameters associated with six northeastward moving Central Plains derechos[a]

hPa	Temperature (°C)		Dew point temperature (°C)		Wind direction (°)		Wind speed ($m\ s^{-1}$)	
	Initiation	Near mid-point	Initiation	Near mid-point	Initiation	Near mid-point	Initiation	Near mid-point
850	21:23	22:24	13:15	10:14	190	208	5:7	12:16
700	10:14	10:12	−1:−5	−3:−5	296	250	6:8	13:15
500	−8:−12	−8:−10	−13:−15	−17:−20	268	266	12:16	18:20
250	—	−42:−46	—	—	261	261	26:30	27:29

[a] Values separated by a colon represent the range of values identified from events.

Unlike southeastward moving northern tier events, the approaching shortwave trough was identifiable through 250 hPa. Over 80% of the events had a visible upper-level trough located west of the initiation region. Two-thirds of the events also formed in the right entrance region of an upper-level jet streak. The trough and associated divergence pattern remained visible throughout the lifecycle of the events, even into the decay region. This demonstrates that northeastward moving events typically form in a more dynamic upper-level environment than southeastward moving DMCSs.

As seen with northern tier events, the downstream environment was more unstable than near the initiation region (Table VII). However, vertical shear profiles are considerably different between event types. Northeastward moving Great Plains DMCSs were associated with higher amounts of 0–3 km shear in the initiation region (Figure 14). This type of shear profile was likely conducive for promoting rotating updrafts with an evolution into a linear MCS (Bluestein and Jain, 1985; Moller *et al.*, 1994).

Vertical cross-sections of θ_e and winds illustrated several characteristics of northeastward moving DMCSs (Figure 15). In over 80% of the events, the strength of the low-level directional shear increased downstream of the initiation region. A majority of the events (83%) also had the highest vertical θ_e gradient occurring from near the initiation region to the mid-point.

5.2.2. Mid-point. Contrary to southeastward moving northern tier derechos, these events remained just ahead of the surface low pressure centre throughout their lifecycle. As expected, the highest surface temperature and moisture values were found near the mid-point. The average mid-point surface θ_e was 336 K and positive θ_e advection was occurring ahead of three of the four events.

A more dynamic environment was found in the low-levels at the mid-point. A trough, moisture transport maximum, and 'nose' of a low-level jet were co-located near the mid-point of the DMCSs and evident at 850 hPa in all events. The maximum along track 850 hPa θ_e near the mid-point was 340 K. The thermal and moisture environment found at the midpoint was similar to southeastward moving northern tier events (Table V). Due to increases in WAA and a shortwave trough axis located west of the mid-point, synoptic-scale lift was maximized at this time in all events. The average 700 hPa quasi-geostrophic omega was $-30\ \mu b\ s^{-1}$. This was significantly higher than what was found at the mid-point of southeastward moving northern tier events.

Table VII. Thermodynamic parameters associated with northeastward moving Central Plains derechos[a]

Time	CAPE ($J\ kg^{-1}$)	Lifted index (°C)
Initiation	1780	−5.4
Near mid-point	3478	−5.6

[a] Three soundings were used to sample the initiation environment and four soundings for sampling the downstream environment.

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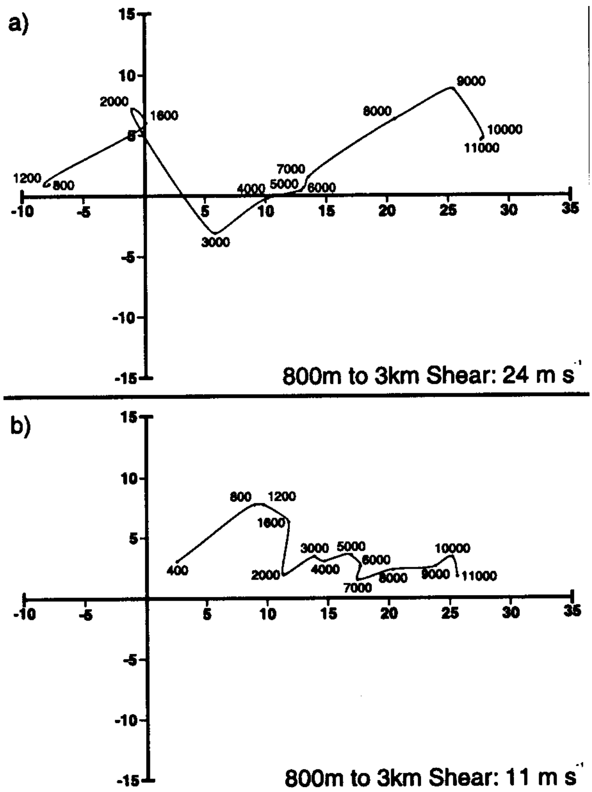

Figure 14. (a) Composite hodograph constructed from three soundings used to sample the initiation environment of northeastward moving Central Plains derechos. (b) Composite hodograph constructed from four soundings used to sample the downstream environment of northeastward moving Central Plains derechos

In the mid-levels, there was a considerable decrease in the 500 hPa dew point temperature between the initiation and mid-point regions (Table VI). This was likely an important factor in maintaining a strong convective-scale downdraft as drier air will act to increase evaporation rates.

An examination of the composite hodographs shows low-level vertical shear weakened in the downstream environment; however, wind velocities increased (Figure 14(b)). Mid- and upper-level flow also became more unidirectional and southwesterly.

Over 80% of the events moved nearly parallel to the 700–500 hPa layer averaged wind field at speeds, on average, of 31% faster than the flow. As the DMCSs approached the decay region, a rightward deviation between 20° and 50° was noted. Overall, 700–500 hPa layer averaged winds are a good predictor of DMCS motion. The rightward deviation in the decay region was likely due to leading edge convergence being maximized along the southern side of the cold pool as the winds became southerly. This caused a rightward propagation of the DMCS.

5.2.3. Decay. Little change was noted in the thermal and moisture environment between the mid-point and decay region. Surface winds appeared to shift to a more southerly flow, which likely decreased leading edge convergence in the decay region.

Even though a shortwave trough was still evident west of all events, only two DMCSs continued to have WAA occurring at 850 hPa and no events had WAA occurring at 700 hPa. Most events (60%) were then located on the east side of a θ_e ridge, having moved through the area of greatest instability and synoptic-scale lift.

Conditions in the mid-levels at the time of decay included southwesterly flow over all the events, which were still travelling east of a prevalent 500 hPa trough. Most of the derechos (60%) were also still located within the upward vertical motion field produced by this trough.

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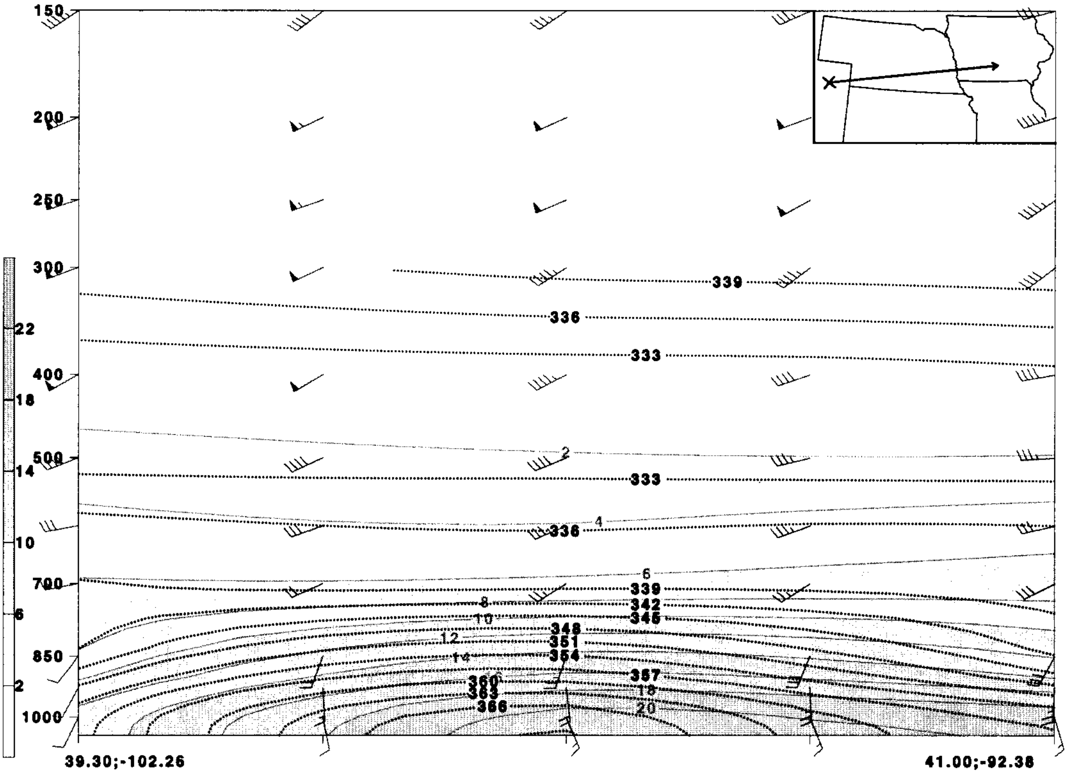

Figure 15. Vertical cross-section of θ_e (K, dotted), mixing ratio (g kg^{-1}, shaded) and winds (knots) for 00:00 h UTC 9 July 1993 (initiation). Derecho track and location for vertical cross-section illustrated with solid arrow

The cross-sections revealed that 60% of the events had passed through the maximum vertical θ_e gradient near the mid-point. In fact, 80% of the events had very little vertical change of θ_e occurring in the decay region. WAA also decreased in intensity over the decay region.

6. SYNOPTIC-SCALE FEATURES OF DERECHO CONDUCIVE ENVIRONMENTS

As shown, distinct synoptic environments produce derechos in the North-Central Plains. The subsequent location and movement of these events also appears to be primarily dependent upon the synoptic environment. Recognition of key atmospheric features is essential in accurately predicting the onset and movement of DMCSs.

Johns and Hirt (1987) developed a derecho checklist to aid meteorologists in identifying important elements in the synoptic environment conducive to DMCS formation (Figure 16). This decision tree would have proved quite useful for predicting southeastward moving northern tier events in this study. These events, which emanate from the northwest flow (NWF) A1 axis, satisfied most elements in the checklist (Johns, 1982; Johns and Hirt, 1987). However, 40% of the DMCSs identified as affecting the North-Central Plains were not located along the NWF A1 axis. In fact, they were *northeastward* moving Central-Plains events. These results suggest an update to the Johns and Hirt (1987) investigation could further assist meteorologists in assessing environments conducive to derecho formation in the North-Central Plains.

Initial diagnosis of a potential DMCS environment begins by determining whether severe convection can be initiated. A high degree of convective instability has been well documented as a common feature of DMCS environments (Johns and Hirt, 1987; Johns *et al.*, 1990; Przybylinski 1995). The average lifted

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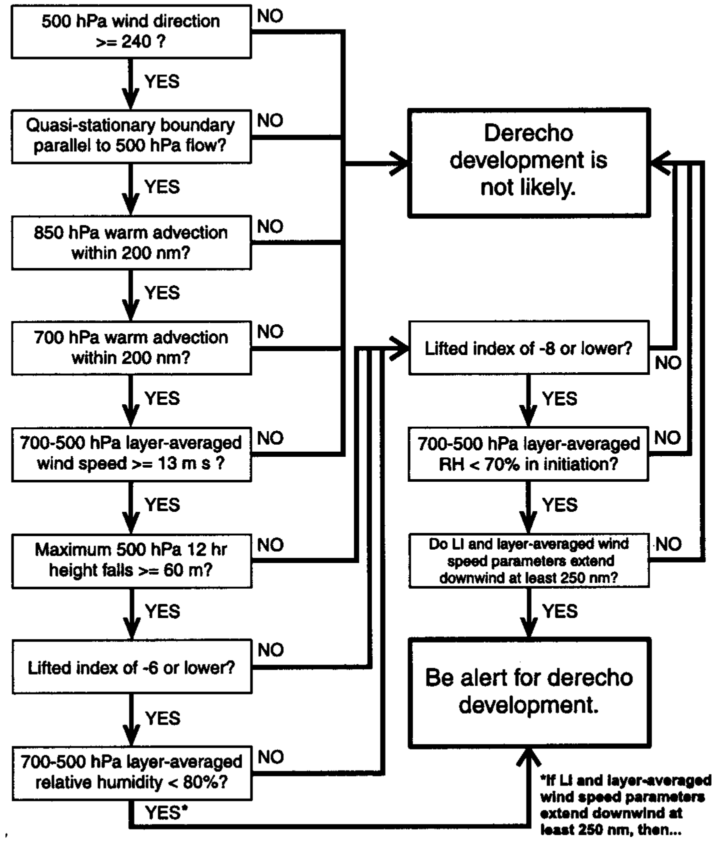

Figure 16. Checklist for forecasting warm season, progressive derecho development (after Johns and Hirt, 1987)

index and CAPE for events in this investigation were $-4°C$ and 2609 J kg^{-1} respectively, with greater instability found downstream. Moderate 0–3 km wind shear (10–18 m s^{-1}) was also seen in the initiation hodographs for DMCS events. These two ingredients are both critical for DMCS formation. If the environment contains moderate shear and is convectively unstable, then the presence of a localized forcing mechanism can act to initiate and organize convection.

During the summer months, shortwave troughs moving through the polar front often provide the localized forcing necessary to initiate and organize convection (Maddox, 1983; Augustine and Howard, 1991). Typically, convective instability is high under the ridge. The approaching shortwave, through the formation of a surface low pressure centre, can circulate a portion of this convectively unstable moist layer out from under the capping inversion, a process called underrunning (Lanicci and Warner, 1991; Bentley, 1997). Nearly 85% of the DMCSs in this investigation formed on the north side of a surface low pressure center along the 'nose' of a θ_e gradient. Evidence suggests that surface low pressure formation along a quasi-stationary front is essential in promoting underrunning and subsequent severe convection in North-Central Plains warm season DMCS environments.

In order for derechos to occur, the synoptic environment must support a convective system capable of producing widespread wind damage along a major axis of at least 400 km. To determine this capability and predict DMCS movement, an examination of the low- to mid-level wind field is necessary. Calculation of the 700–500 hPa layer averaged wind field has proven to be a useful predictor of DMCS movement (Johns and Hirt, 1987). In this investigation, the DMCSs deviated slightly to the right of the flow as they travelled away from the initiation region. This characteristic is partly due to the weakening of the capping inversion along the DMCS track (Johns and Hirt, 1987). The systems appear to build southward toward the quasi-stationary boundary as the lift required to break the capping inversion decreases. Another key element present in derecho environments is the nearly parallel orientation of the quasi-stationary boundary to the mid-level flow (Johns and Hirt, 1987). DMCSs typically move along the surface boundary in the direction of the mid-level layer averaged flow. This is likely due to the importance of the relationship between the convectively induced cold pool and vertical shear.

Cold pool strength is determined by two main elements present in the synoptic environment: CAPE and the moisture content of the low- to mid-troposphere (Rotunno *et al.*, 1988). Evaporative cooling, the presence of drier mid-tropospheric air and precipitation loading in the downdraft strengthens the cold pool and fortifies the formation of a mesohigh (Rotunno *et al.*, 1988; Houze *et al.*, 1989). The cold pool produces a significant circulation, which left unbalanced would disrupt the overall organization of the system. Results from numerical models suggest moderate to strong low- to mid-level vertical shear in the ambient environment counteracts this negative feedback leading to a strong, long-lived DMCS (Weisman, 1992). However, recent investigations into observed shear profiles associated with long-lived bow echoes yield contradicting results (Evans, 1998). In this investigation, a weak to moderate shear profile (9–14 $m\,s^{-1}$) was commonly observed in hodographs taken near North-Central Plains DMCSs. This supports recent findings that other mechanisms in the DMCS environment might assist in balancing cold pool circulation and lead to upright convection (Bernardet and Cotton, 1998; Evans, 1998). The component of environmental shear perpendicular to the line orientation (line-normal shear) is the most critical for controlling MCS structure and evolution. Unidirectional, line-normal flow occurs throughout the mid- and upper-levels of the DMCS environment.

Once DMCS movement is estimated from the layer averaged winds, diagnosis of the downstream environment should be made. Increasing convective instability and vertical shear depth were evident in along-track soundings. However, it is interesting to note that for southeastward moving DMCSs, the CAPE remained nearly the same between initiation and mid-point soundings while the LI increased considerably (Table V). Conversely, for northeast moving DMCSs, the opposite occurred (Table VII). Since 850–500 hPa temperatures were similar for both DMCS types, it appears differences in the makeup and evolution of the boundary layer were responsible for changes in CAPE and LI.

Cross-sections along the DMCS track were also found to be useful in assessing the potential of the synoptic environment to support DMCSs. A tight vertical θ_e gradient, decreasing with height, was evident in the majority of events. Drier mid-level air overlying moist surface air leads to strong convective-scale downdrafts and has been identified in other bow echo and/or derecho environments (Johns *et al.*, 1990; Atkins and Wakimoto, 1991; Corfidi, 1998). The strong convective-scale downdrafts and mesohigh formation common in DMCS environments produces a gust front that moves faster than the mean flow (Corfidi, 1998). In this investigation, the DMCSs moved an average of more than 30% faster than the 700–500 hPa layer averaged wind speeds. This high translation speed maximizes leading edge convergence on the down-shear side of the DMCS. Likewise, convective forcing in this area produces a forward propagation of the system. In environments containing deeper layer moisture convective forcing along the gust front is much weaker and low-level convergence occurs up-shear, leading to a quasi-stationary MCS (Maddox *et al.*, 1979; Juying and Scofield, 1989).

Diagnosis of the strength and depth of the along track WAA is also aided by examining cross-sections. The quasi-stationary boundary provides a thermal gradient across which low-level WAA developed in the majority of the events. The WAA is a source of upward vertical motion realizing the potential energy of the convectively unstable air along and south of the boundary (Maddox *et al.*, 1981; Maddox, 1983; Augustine and Howard, 1991).

Temperatures at 500 hPa are somewhat cooler then average, representative of a severe thunderstorm environment (Johns, 1984). The composite hodographs and idealized sketches of the synoptic-scale situations favourable for DMCSs emanating from specific corridors should assist meteorologists in determining when the mid- to upperlevel flow is in a favourable alignment.

The diagnosis of key elements in the DMCS environment are further assisted by utilizing newer technologies currently available. Real-time mesoscale models (e.g. RUC, meso-ETA) combined with the Advanced Weather Information Processing System suite of analysis products should improve short-term forecasting of derecho events. It is hoped that this investigation builds upon previous studies and further elucidates features of the derecho environment occurring in the North-Central Plains.

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