INITIATION, EVOLUTION, AND DEMISE OF DERECHO PRODUCING MESOSCALE CONVECTIVE SYSTEMS

by

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CHAPTER I

INTRODUCTION

The first known use of the word "derecho" to describe weather phenomena occurred in 1888. An Iowa weather researcher Gustavus Hinrichs used the term to describe damage cause by non-tornadic convective windstorms. Derecho is a Spanish word and may be interpreted as "straight on" or "straight ahead." Hinrichs chose derecho to describe straight-line winds to differentiate them from convective storms producing tornadoes. Many revisions to Hinrichs definition have occurred throughout the years as investigations of these systems have taken place.

Derechos and convective windstorms in general have long been discussed in the literature and have been responsible for considerable damage across the U.S. and numerous casualties every year. Although the convection responsible for damaging surface winds varies in strength and size, derechos account for the most severe and widespread damage. Wind damage caused by derechos is largely underrated in the eyes of the public. Many believe the biggest threats from thunderstorms are tornadoes, hail, and lightning. Straight-line winds; however, may have an impact just as detrimental as other types of events, depending on the location and overall severity. During 30-31 May 1998, a derecho moved across Minnesota, Wisconsin, and Michigan, killing 5 and injuring 211, while producing $280 million dollars in damage. By comparison, during July 1997, hurricane Bertha made landfall in North Carolina as a category 2 storm causing $270 million in damage (Bentely et al., 2000).

It is important to understand how, when, and where derechos form due to the potential risk to life and property. From January 1995 to July 2000, convectively generated wind storms produced over $1.4 billion in property damage, 72 deaths, and 1008 injuries as reported to the National Weather Service. Keep in mind that only a small percentage of actual damage is reported. Golden and Snow (1991) estimated that between $1 billion to $3 billion dollars of property damage occurs annually. It is therefore important to educate the public on the hazards associated with derechos to potentially mitigate the severity of these systems with proper preparation as the system approaches. Even though derechos are not as life-threatening as tornadoes, they tend to affect a larger portion of the population and inflict more minor damage over a much larger extent. However, it should be noted that tornadoes occur quite frequently with Derechos. Johns and Hirt (1987) determined that 81% of derecho events are accompanied by at least one tornado, while 26% of the cases produced 6 or more tornadoes. Tessendoff and Trapp (2000) found that squall-line/bow echo tornadoes account for up to 20 percent of all tornadic events nationwide. Also, contrary to popular belief, such tornadoes can be quite strong and long-lived. It is important to understand how to forecast derecho events, not only because of the severity of derecho events, but also because of the large percentage of summertime rainfall attributed to them. Fritsch et al. (1986) found that MCCs (Maddox, 1980) contribute to as much as 20%-50% of the annual rainfall over a large portion of the Central Plains, of which, derechos are a subset.

This thesis will look at synoptic conditions associated with derechos to determine in what type of environments these systems form. Evaluation of synoptic conditions that favor the continuation and demise along the path of the derecho is also completed. Findings are compared with that of previous climatological studies. Also, radar imagery is analyzed in an attempt to determine what convective features within a derecho are responsible for the associated severe winds.

CHAPTER II

LITERATURE REVIEW

Derecho Definition and Classification

Mesoscale Convective Systems (MCSs) are common across the central and eastern United States, especially during the summer months. MCSs are normally composed of multiple thunderstorm cells or families. MCSs have been related to a high frequency of severe weather, including tornadoes, hail, high winds, and flash floods. In general, a derecho is merely a subset of MCS, a Derecho Producing Mesoscale Convective Systems (DMCS). Derechos have been defined as a family of downburst clusters with temporal and spatial continuity and a major axis length of at least 400 km (Fujita & Wakimoto, 1981) and are produced by an extratropical MCS (Johns & Hirt, 1987). Derechos typically have a lifecycle between 6 and 12 hours, but have been known to endure for upwards of 20 hours. These systems may take on a number of forms ranging from squall lines to cloud clusters to mesoscale convective complexes (MCC) (Maddox, 1980). Utilizing severe wind report data, Johns and Hirt (1987) put forth the following criteria to distinguish derecho events from typical MCSs:

(a). Wind reports must show a chronological order.

(b). Must be at least three wind reports of either F1 damage or wind gusts of greater than 34 m/s (65 kt); reports can be separated by no more then 64 km.

(c.) No more then 3 hours can elapse between successive wind reports.

(d.) The associated MCS must have temporal and spatial continuity.

(e.) Damage swaths of wind or wind gusts must be part of the same MCS as indicated by radar imagery.

Bentley and Mote (1998) have since proposed refinements to criteria set forth by Johns and Hirt. They are as follows:

(a). The criterion that there need to be at least three wind reports of either F1 damage or wind gusts of greater then 34 m/s (65 kt) was not used. However, again severe wind reports can be separated by no more then 64 km.

(b). Wind reports must show a chronological order.

(c). No more then 3 hours can elapse between successive wind reports, was changed to no more then 2 hours.

(d). The associated MCS must have temporal and spatial continuity with no more then 2° of latitude or longitude separating successive wind reports.

(e). The wind reports of each event are mapped to determine spatial continuity.

(f). There must be a concentrated area of convectively-induced wind gusts greater then 26 m/s (50 kt) with a major axis of at least 400 km.

(g). Radar imagery is not used to validate wind reports were from the same MCS.

The main factor in categorizing a storm system as a derecho is the length of the major axis. It is extremely rare for a single thunderstorm to last long enough to travel 400 km and produce an adequate number of high wind reports. Therefore, a derecho will form almost exclusively from a MCS.

Based on examination of radar summary charts, Johns and Hirt (1987) found at least two types of derechos, which can be classified as progressive and serial.

Progressive derechos (Figure 2.1) are characterized by a short, curved squall line oriented normal to the mean wind flow, in which there is a bulge in the direction of the flow. Closer examination of these echoes many times will show a number of smaller bow echoes evolving within the main bow echo. It has been shown the most frequent region of severe wind occurrence is near the apex of the eastward bulging line (Fujita & Wakimoto, 1981). Numerical modeling efforts of Trapp and Weisman (2003), however, suggest some of the most severe and longest lasting winds occur northwest of the bow apex. These severe winds are related to mesovortices near the end of individual line segments or bookend vortices; however, at times vortices were also found to exist within the squall line. It has also been determined that the progressive derecho is the most common type with a 76% frequency and occur extensively during the warm season (May-August) (Johns & Hirt, 1987). Evans and Dowell (2001) also concluded warm season derechos are the most common, as have other studies. Progressive derechos generally form under relative benign synoptic conditions or what is considered weak synoptic forcing (Figure 2.2) (Evans & Doswell, 2001). Serial derechos (Figure 2.3) are found to be oriented nearly parallel to the mean flow such that a small angle exists between the mean wind direction and the axis of the squall line. The squall line itself is usually quite extensive and may cover upwards of 1000 km; within the line numerous smaller bowing segments exist. Due to the more discrete single-cell nature of the convection, damage usually appears in multiple separate swaths, hence, a serial derecho. Serial derechos form under dynamic synoptic conditions or strong synoptic forcing events (Figure 2.4) (Evans & Doswell, 2001). They also determined a third type of

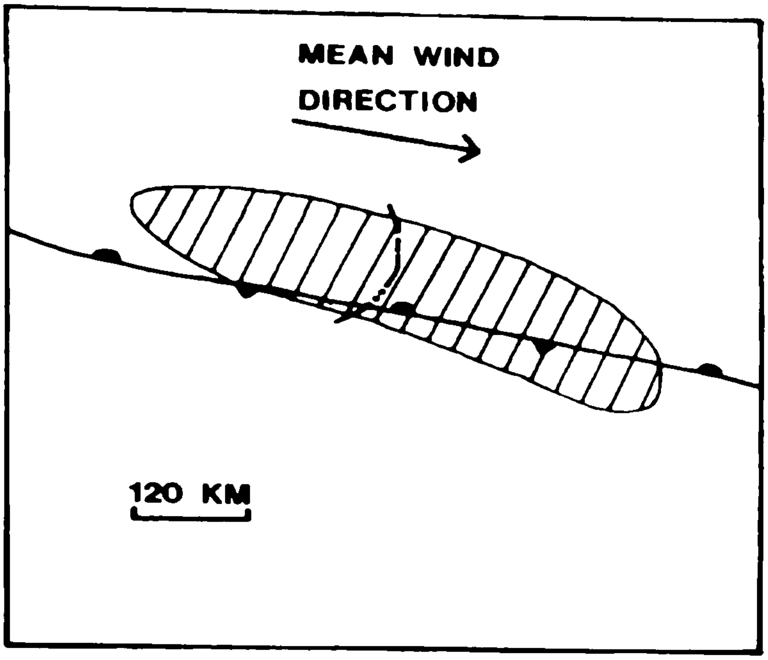

Figure 2.1. Conceptual view of a progressive derecho and associated features near the midpoint. Hatching show area affected by the derecho. Squall line and stationary front are also shown. (Johns & Hirt, 1987)

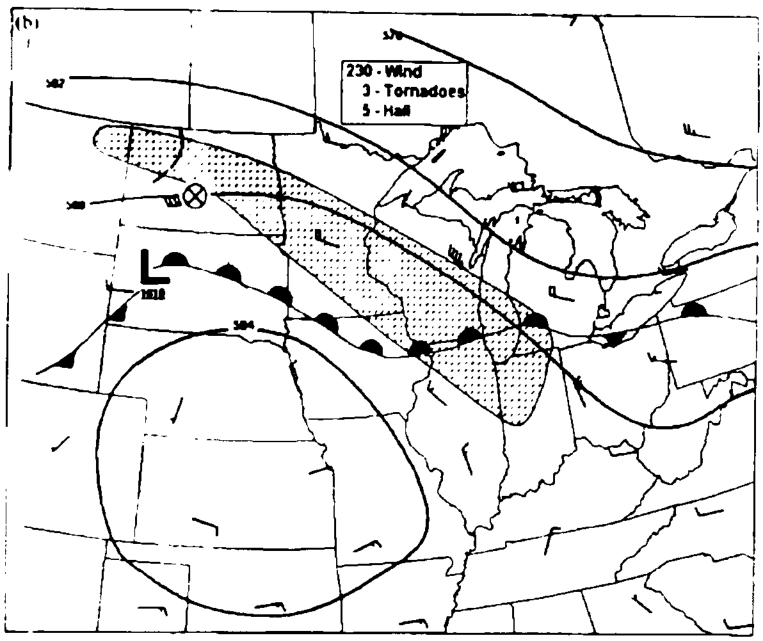

Figure 2.2. Typical synoptic pattern associated with warm season (weak forcing) progressive derecho events. Shaded area represents the derecho path, while dashed line shows its position. 500 mb height contours and wind barbs are show as are surface features. (Evans & Doswell, 2001)

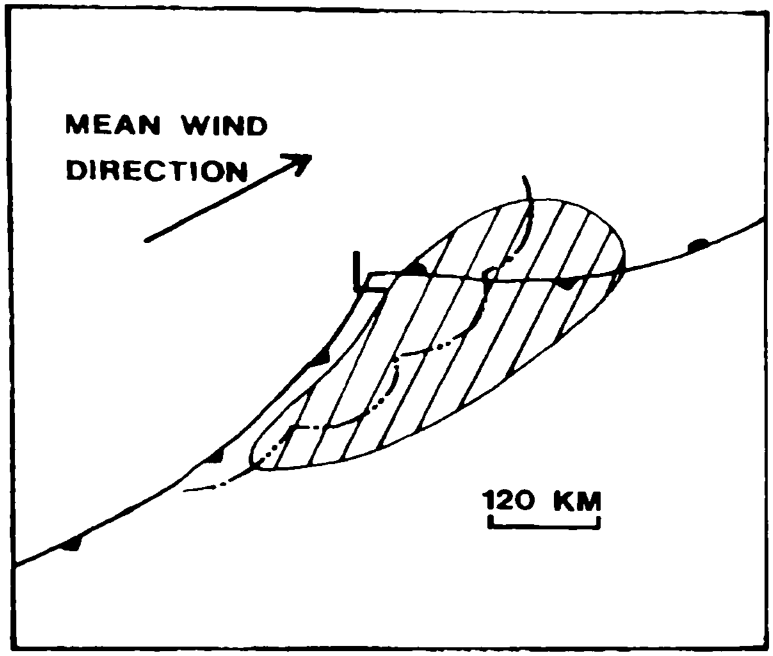

Figure 2.3 As in Figure 2.1, except schematic depicts features associated with a serial derecho. (Johns & Hirt, 1987)

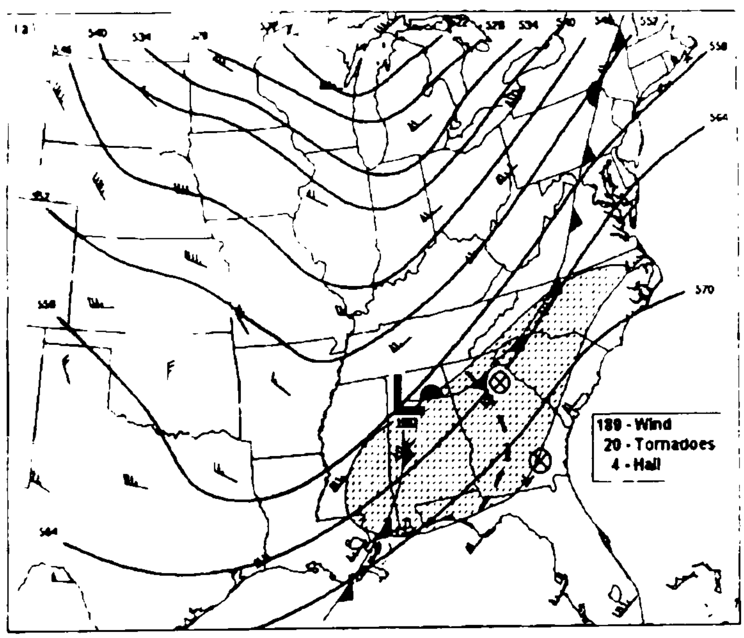

Figure 2.4. Similar to figure 2.2 except image represents a strong forcing (cold season) serial derecho event. (Evans & Doswell, 2001)

derecho or a hybrid type (Figure 2.5) in which synoptic conditions did not clearly fit either the strong or weak forcing categories.

Derechos can take on many different forms and since nearly 90% of MCSs (Gale et al. 2002) and virtually all derechos take on a linear form during their lifetime, the easiest way to distinguish the type is to use radar reflectivity patterns. Przyblinski and Dexaire (1985) have identified four different radar signatures that derechos usually assume. The common characteristics for each type include the presence of bow echoes, a strong low-level reflectivity gradient along the leading edge. Also, all types indicate weak echo notches (WEN) or distinct regions of lower reflectivity trailing the squall line. These regions are also denoted as rear inflow notches (RIN) and are recognized as a signature depicting where a rear inflow jet emanating from the midlevels may exist. This also signifies a region of evaporatively cooled lower θ_e air caused by dry air entrainment

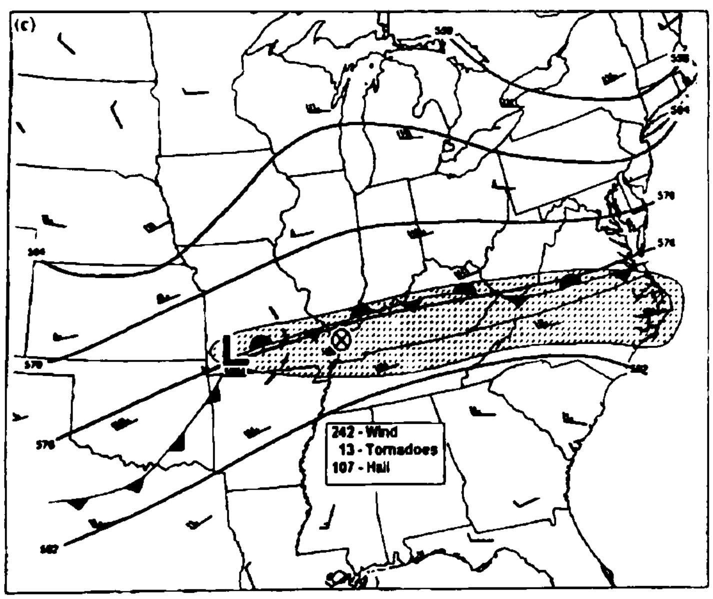

Figure 2.5. Same as Figure 2.2 and 2.4, except this schematic shows a derecho pattern related to a hybrid derecho, which cannot be classified as weak or strong forcing event.

in the midlevels. The type I DMCS (Figure 2.6) is in general characterized by two to three bowing line segments, each of which cover upwards of 100 km. Each segment is likely accompanied by a mesocirculation at the ends of each bowing segment. Type II is characterized by a short, solid and bowing convective line segment between 80 and 100 km in length. This type can be uniquely identified by an isolated convective thunderstorm downstream from the main convective line. Type III have a solid bowing line extending between 40 and 120 km in length and unlike type II do not have an isolated storm downstream. Type III produces a strong embedded cell with supercell characteristics that may persist while the bow echo continues to evolve. Type IV systems usually begin as an intense storm evolving through the classic high-precipitation (HP)

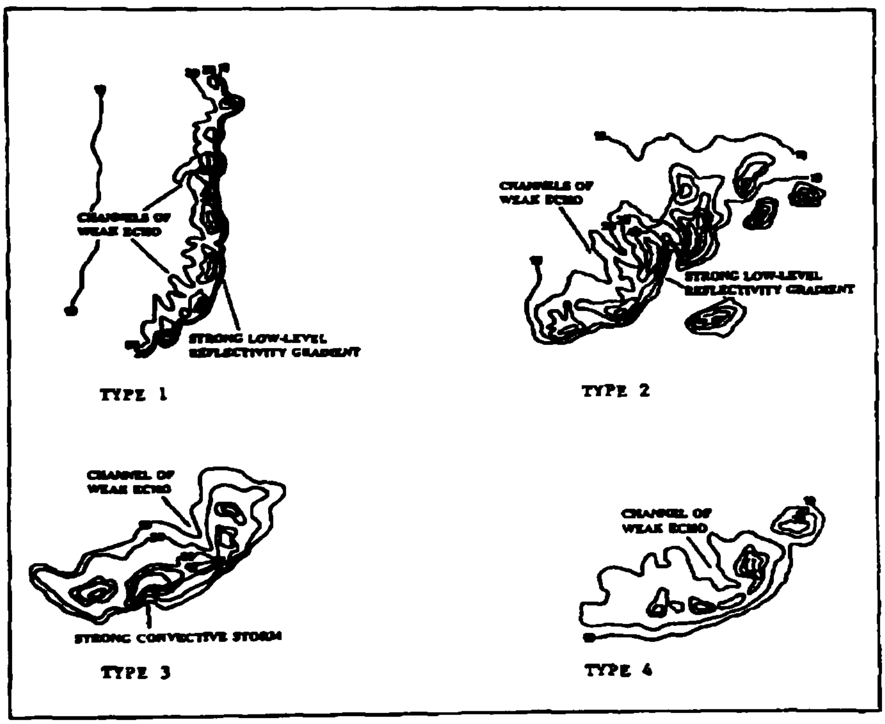

Figure 2.6. Diagrams of radar signatures related with derechos. Solid lines represent radar refletivity values (DBZ). (Przyblinski, 1995)

supercell life cycle (Moller et al., 1990). Many times the storm will develop a bow echo structure as convection forms along the rear flank downdraft. It should be noted that these are only common forms of radar signatures associated with derechos, hybrids and combinations of these types may form.

Climatology

Numerous studies have been completed to determine the climatology associated with derechos in the United States. Johns and Hirt (1987) found a high frequency of warm season derechos extending from eastern South Dakota to Central Ohio (Figure 2.7). This study comprised of 70 warm season derechos from 1980-1983. Bentley and Mote (1998) also found a distinct maximum in warm season events (Figure 2.8); however, over a 10-year period from 1986-1995, the highest frequency occurred over the Southern Plains, with the highest occurrences over Kansas and Oklahoma. An explanation of these discrepancies has since been proposed by Johns and Evans (2000). They believe the removal of the 33 m/s wind gust criterion and a denser wind report criterion allows for deficiencies of the convective wind report database to have a larger effect on the results. They also believe removal of radar examination to verify storms are from a single MCS may allow for clusters of individual thunderstorms or isolated supercells to contaminate the data set. They also questioned the adequacy of a 10-year period to depict the true climatology. Bentley and Mote (2000a) replied by arguing the 33 m/s wind gust criterion is not required because no reference to wind gust magnitude was made by Fujita and Wakimoto (1981) within their definition of downburst clusters. Also, wind gust and

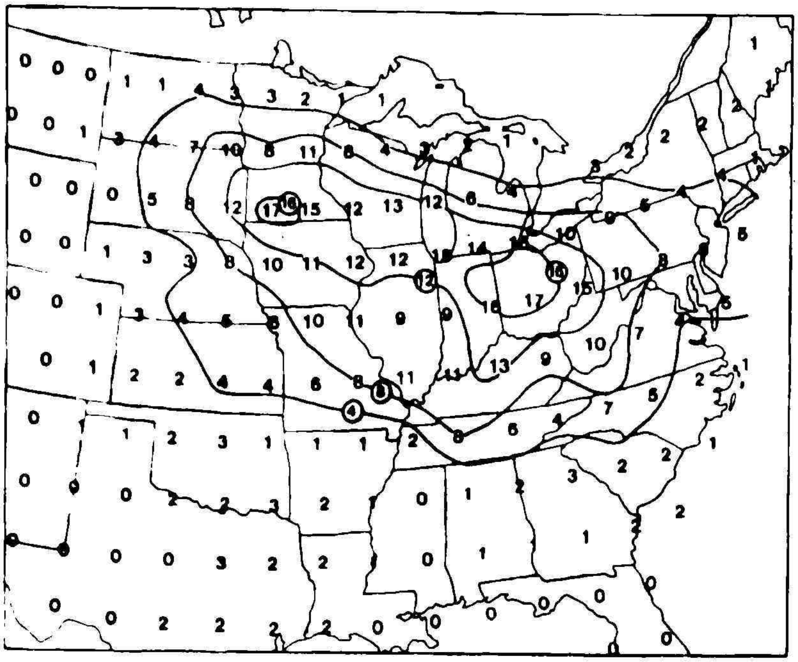

Figure 2.7. Total number of warm season (May through August) derecho occurrences over the 1980-1983 time period. (Johns & Hirt, 1987)

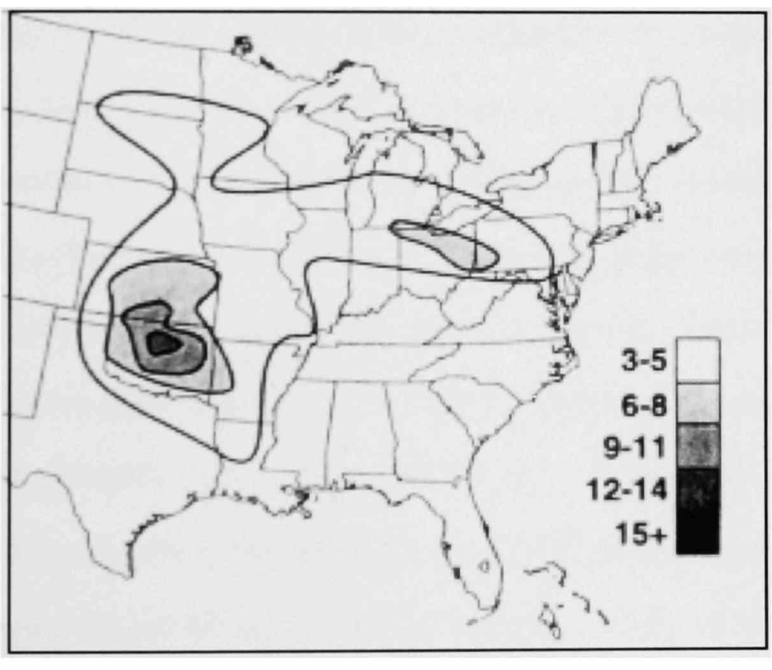

Figure 2.8. Similar to figure 2.7, except shows the total number of warm season derechos from 1986-1995. (Bentley and Mote 1998)

damage estimates from the Storm Prediction Center are in many cases just that, estimates, which can lead to many inaccuracies, regardless. They also believe the parent convective complex should not restrict the definition of a derecho. Finally they believe the Johns and Hirt (1987) climatology was skewed by an anomalously strong ridge in the central U.S. during that study's time period, leading to a higher frequency of storms across the upper Midwest and Ohio Valley. A more recent study of 188 derechos from 1996-2002 again shows a primary frequency axis in the upper Midwest and Ohio valley (Bentley & Sparks, 2003). However, they found there also exists a relative frequency maximum over the Southern Plains. They attribute the shifts in derecho frequency during different time periods to be related to the overall synoptic pattern; this was found to be especially true for warm season events. This suggests that derecho formation is highly dependant on synoptic conditions. All of the previous studies found there to be a northward progression of derecho occurrences during the warm season, with the DMCS frequencies retreating south later in the year. It should be noted that derechos can form anywhere east of the Rocky Mountains, provided an ample source of moisture and a lack of physical barriers to allow for long lived self-sustaining convective systems.

Derechos can occur at any time of the day; however, most derechos initiate between 1600Z and 0400Z (Johns & Hirt, 1987; Bentley & Mote, 1998). In many cases this happens a number of hours after the initial convection begins. Although derecho formation is most common during daytime hours, especially in the late afternoon and evening, these systems typically last well into the overnight and many times into the next morning.

Initiation Environment

Synoptic environments that support derechos have been well documented through a number of case studies. Johns and Hirt (1987) found that derecho environments were characterized by large amounts of moisture at low levels and extreme instability with an average lifted index of -9, notwithstanding lesser instabilities were possible when accompanied by strong upper-level shortwave troughs. Convective Available Potential Energy (CAPE) values are also generally quite high prior to derecho formation with values ranging between 2000 to 3000 J/kg (Johns & Hirt, 1987, Evans & Doswell, 2001). However, Evans and Doswell (2001) also found a large variance in CAPE values and warn forecasters that derechos can form with extremely low values provided strong synoptic forcing. This is especially true with nocturnal derechos as surface-based instability may be quite low or non-existent. In these situations it has been found that there is initially an unstable layer above the surface near the initiation point. The triggering mechanism for this type of convection (elevated convection) is large-scale forcing. These systems cannot maintain themselves, especially in the absence of strong synoptic scale forcing, unless a continuing supply of energy is provided to the system. This occurs two ways, either the low-level jet (LLJ) provides a flow of warm moist air into the system or stable surface air is forced into the system along the leading edge of the cold pool.

Studies have shown warm season derecho formation occurs north of a surface thermal boundary, which is oriented parallel to the mid and upper-level flow. Serial derechos tend to form along or near the surface warm front or along the surface cold front. In a study of 110 bow echo events, Klimowski et al. (2000) also found that roughly half formed within 50 km of a mesoscale outflow or preexisting thermal boundary. The highest surface convergence was also found to exist along this boundary and near to the genesis point of most DMCSs. The initial thunderstorm activity starts a few hours before the bow echo develops, usually in the region along the front, which has the greatest low-level warm advection and pooling of moisture (Johns, 1993). In most cases (74%), pooling of low-level moisture takes place at the surface and in the lower levels near a quasi-stationary boundary (Johns & Hirt, 1987). A tight horizontal θ_e gradient that decreases with height, is also a feature associated with many derechos (Bentley et al., 2000), as the upper levels tend to be uniformly dry.

At upper levels the flow pattern becomes important to the formation and evolution of derechos. Johns (1993) finds that for long-lived bow echoes the mid and upper-level flow is often westerly to northwesterly. However, in the strongly forced environments described by Evans and Doswell (2001) the derecho is formed in front of a high amplitude midlevel trough and in conjunction with a strong surface cyclone. There is generally anticyclonically curved flow found at levels above the genesis region (Johns et al., 1990).

Shear is also important for derecho formation, but if it is too great, then only discrete supercells will be able to survive. For long-lived damaging wind events, numerical cloud modeling study performed by Weisman (1993) suggest 20 m/s of shear is needed for optimal sustained bow echo development. Trapp and Weisman (2003) showed that Quasi-linear Convective Systems (QLCS) exist in environments with 0-2 km and 0-5 km shear values between 10-30 m/s, provided surface-based CAPE values of 2200 J/kg. Evans and Doswell (2001) found that the majority of the derechos they studied had shear values within the accepted range for non-tornadic supercells and some had values less than 15 m/s.

Evolution

An idealized evolution of a bow echo capable of producing strong downburst winds is shown in Figure 2.9. Since derechos are usually made up of multiple bow echoes that are evolving in much the same way, there can be many damage paths associated with the same system. Contributors to these strong, "straight-line" winds include mesohighs (Johnson & Hamilton, 1988) and downbursts (Fujita & Wakimoto, 1981). Straight-line winds have also been found to occur near the apex of the bow echo (Fujita & Wakimoto, 1981) and are thought to be produced when the rear inflow jet contacts the surface just behind the leading edge of the gust front (Weismann, 1993) or by the gust front itself (Wakimoto, 1982). However, it has been noticed that in numerous instances, severe wind damage also occurs northwest of the apex, frequently causing damage over a broad area. In theses situations, the position of these winds in relation to the bow apex nearly rules out a rear inflow jet as the cause of the severe winds, and the large coverage of damage would rule out downdrafts, especially smaller downdrafts such as microbursts. A percentage of these severe "straight-line" winds may transpire from surfaced-based mesocyclones, which could create large horizontal pressure gradients, thus inducing an acceleration of the horizontal wind. Trapp and Weisman (2003) used

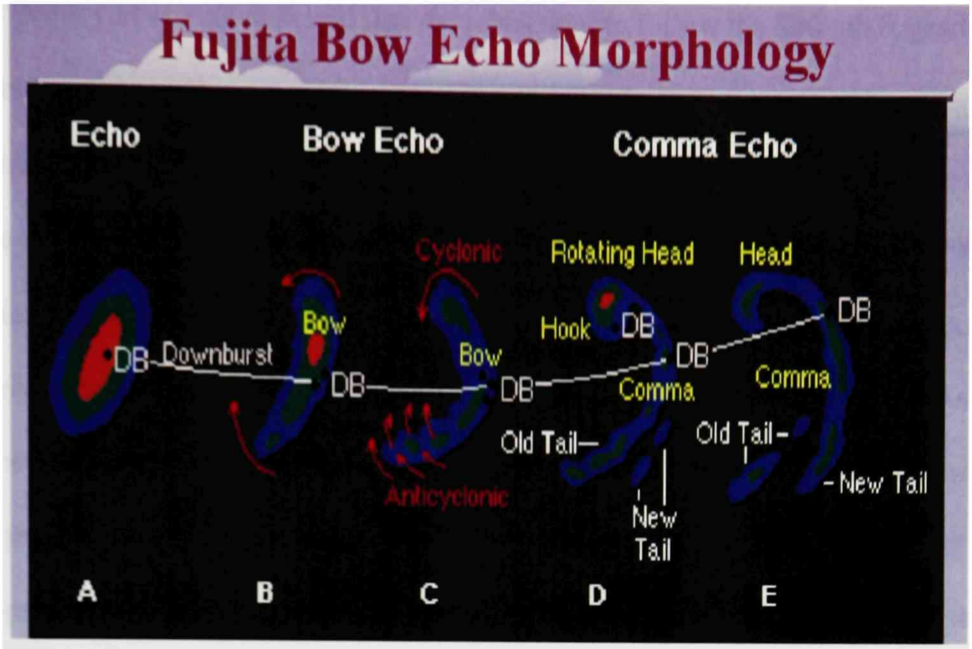

Figure 2.9. Typical evolution of radar imagery associated with strong and extensive downdrafts (Modified from Fujita 1978)

numerical cloud models to show numerous surfaced-based mesocyclones can exist within a bowing line or line segment. These mesocyclones are formed when horizontal vorticity is tilted by either an updraft or downdraft. This is likely the cause for bookend vortex development, although, another theory would suggest the rear inflow jet and cold pool expansion are the leading factors in the vortex formation. Following formation, anticyclonic vortices have been found to decrease in intensity over time while the cyclonic counterpart intensifies. Numerical models suggest planetary vorticity to be responsible for cyclonic (anticyclonic) vortex growth (decay) (Weisman & Trapp, 2003). The northern end of the squall line has been found to be associated with a higher frequency of tornado creation, undoubtedly related to development of the stronger cyclonic mesovortex.

Ashley et al. (2000) found that derechos tend to follow the 850 mb θ_e gradient. This gradient is usually in line with the surface temperature boundary and has warm air and moisture advection associated with it. Derechos usually move parallel to the thermal surface boundary while curving slowly towards the warm sector (Johns et al., 1990). With time, however, the derecho moves into an area where the low-level flow becomes more parallel to the upper level flow and warm advection may weaken or end. As this happens, the gust front associated with the system becomes the primary mechanism for lifting parcels into the storm (Johns et al., 1990). They also state that the derecho develops its most damaging winds as it moves into the most unstable air in its path. CAPE values also tend to increase as the system moves to the east to an average maximum of 4500 J/kg compared to an average genesis region CAPE of 2600 J/kg.

Decay

Generally speaking, decay and dissipation of DMCSs have not been well addressed in the literature. The main focus has been placed on the predicting the formation of these systems, which in itself is a daunting task. Forecasting dissipation is no less formidable, as there are a number of factors that likely contribute to the demise of a derecho. There is thought to be a large dependence on the LLJ for derecho development and maintenance. As a DMCS travels east, the low-level jet, which during initiation stages, is usually oriented perpendicular or close to perpendicular to the upper-level jet. Over time, the LLJ becomes more zonally oriented or parallel to the upper flow. This serves to weaken the environmental shear and the system begins to die, as documented by Ashley et al. (2000). Although, Evans and Doswell (2001) found derecho environmental 0-3 km shear values ranging between 3 and 30 m/s and an even larger range for 0-6 km with shear vector magnitude between 1 and 36 m/s. Evans (1998) and Gale et al. (2002) noted similar results. These findings imply that environmental shear is not likely the main contributor to DMCS development, much less an explanation for dissipation. The main contribution of the LLJ is that in many cases it is the main source of sustenance. If the LLJ slows down or becomes separated from the convective system, the warm moist unstable air source is lost. However, in many instances, derechos continue to thrive as the LLJ becomes weak to nonexistent. Gale et al. (2002) found that 10% of MCSs have no low-level jet association during any portion of the life cycle. They also found there exists a stronger relation between LLJ termination and MCS dissipation than LLJ weakening and MCS dissipation. Many times unstable air is brought into the systems as the leading edge of the cold pool advances, forming new convection along the gust front as unstable boundary layer air is forced into the system. Thus, although the LLJ may be crucial in maintaining some DMCSs it is likely a negligible factor in a number of cases, especially provided the system has an ample supply of moist boundary layer air.

Weakening also can occur if the system moves into a stable air mass, although this may not affect the system if it has become elevated or if the low-level jet remains strong. In some cases stable air may be the result of previous convection. Johns et al. (1990) and Bentely et al. (2000) found that the ingestion of moister air at mid-levels is a contributor to the death of the derecho as this helps decrease instability and weaken downdraft formation, thus weakening the cold pool. This also explains why air mass instability either at the surface or above the boundary layer is quite important in both the genesis region and the region into which the derecho propagates.

When examining data from the ETA model, Gale et al. (2002) found that most parameters showed little to no potential as indicators of MCS demise. These included environmental wind speed, convergence, moisture convergence, frontogenesis, θ_e values, 500 mb vorticity advection, and 250 mb divergence. They found that only θ_e advection showed promise as a dissipation predictor. For 80% of southeast moving derechos, Bentely et al. (2000) noticed a decrease in the θ_e gradient during decay, with all events decaying on the east side of the 850 mb θ_e ridge. This differed for northeastward moving derechos where little change was noted in the thermal and moisture structure from the mid-point of the system to the decay region. In fact, 80% of derechos with northeastward motion showed no θ_e gradient. Moisture and stability appear to be the most crucial factors in derecho formation and decay. If there exists an ample supply of unstable moist air over a large extent then a derecho may be a very long lived.

CHAPTER III

DERECHO CASE STUDIES

For this study four derecho events were examined. Three of the events were warm season derechod with weak forcing, while one was of the hybrid type as described by Doswell and Evans (2000). Two events occurred in the Northern Plains, while the other two traversed the Central and Southern Plains to the Gulf of Mexico. All the events were chosen by examining the Storm Prediction Center (SPC) archived severe wind reports. When a large number of severe wind reports were found in the same general region on the same day, then the wind data were checked to ascertain that they met the criteria set forth by Bentely and Mote (1998). Once all criteria were satisfied archived radar data were analyzed to verify that wind events emanated from the same convective complex. Using the ETA model analysis for each event, a synoptic summary was then completed. Archived ETA model data were acquired from the National Center for Atmospheric Research (NCAR). ETA model data were in grib format and displayed using the Grid Analysis and Display System (GrADS). ETA analysis was available as frequently as every three hours, allowing for adequate time resolution of the large-scale features associated with each event. This chapter includes an ad hoc synoptic overview of atmospheric conditions preceding the derecho events as well as details for initiation, evolution, and demise. Findings are compared to that of previous derecho studies in Chapter IV.

Case I

Synopsis

On 8 August 2001 at approximately 06Z a derecho initiated in east-central North Dakota (ND) continuing across northern Minnesota (MN) and the upper peninsula of Michigan (MI). Eventually it traveled southeast across Lake Michigan into lower MI where the last severe wind reports occurred (Figure 3.1). The first observable convection as depicted by radar materialized at 18Z 7 August over extreme northeast Montana (MT). Subsequently a convective complex formed around 0Z 8 August over central ND. This is approximately six hours before the first report of severe wind. This is typical as 88% of derechos develop a convective complex at least three hours before derecho initiation and 57% more than six hours prior (Johns & Hirt, 1987). The first report of severe wind (58 kt) occurred at Buffalo, ND, at 0550Z as a relatively compact DMSC traveled eastward. At 0620Z the Davis System at Hillsboro, ND, measured an 87 kt sustained wind with a 96 kt gust. Numerous winds reports continued across northeastern MN ranging between 52-75 kt. The severity of wind reports subsided for the remainder of the DMSC life with most reports around 55 kt. The last wind report occurred at 2140Z in southeastern Michigan (MI).

The duration of this derecho was 19 hours; and it had a major axis of nearly 1300 km. Fifty severe wind reports occurred over the lifetime, not a high number, but this is likely due to the scarcity of population. This was a progressive-type derecho, which is evident by the bow on the leading edge of the storm. Convective development was mainly ahead of the convective complex but some originated along the southern flank.

Figure 3.1. Blue squares represent severe wind damage or wind gusts 50 kt or greater during Case I.

Environment

At 1800 on the 7 August a surface ridge was in place over MN while a low pressure trough extended through the western Dakotas. Lifted indices over western ND were as low as –4, with Convective Available Potential Energy (CAPE) both indicating some instability (CAPE output from ETA is surfaced-based CAPE). A strong Convective Inhibition (CIN) or cap was also present, which would typically preclude convective development. However, synoptic-scale forcing was also present, eventually leading to the development of convection. An upper-level short wave (Figure 3.2) was moving through westerly flow aloft in conjunction with θ_e overrunning at 700 and 850 mb. The upper-level jet was positioned quite far north over central Manitoba (MB). By 0Z on 8 August diabatic heating during the afternoon along with warm air advection (WAA) created extremely unstable conditions across eastern ND. In places surface temperatures exceeded 100° F with dew points approaching 80° F (Figure 3.3). This in tandem with synoptic forcing allowed for convection to flourish. Once the derecho

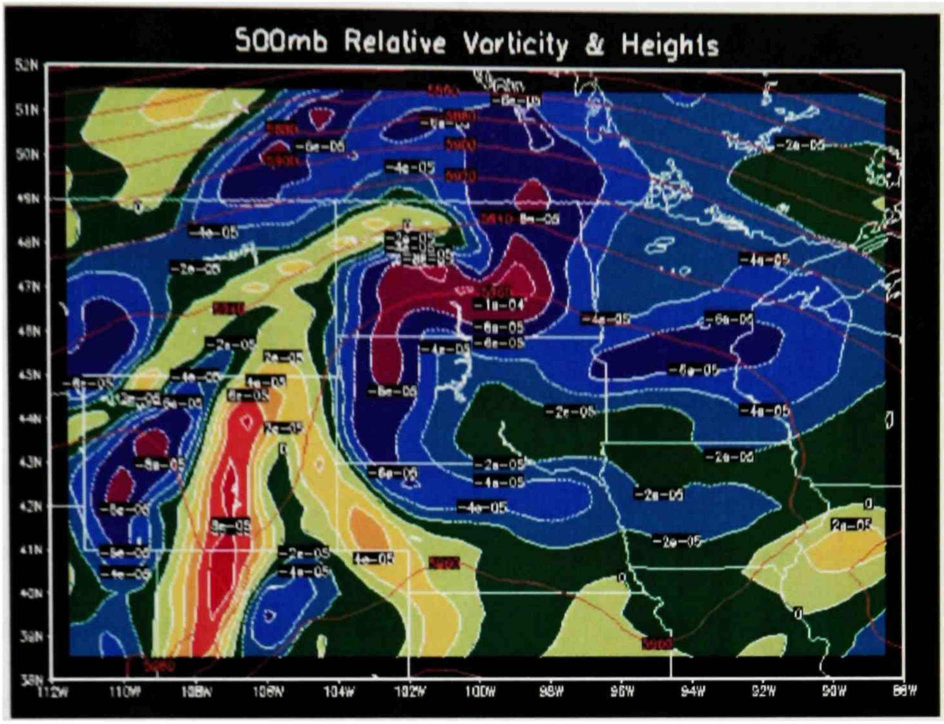

Figure 3.2. ETA analysis at 0Z 8 August 2001 with cool (warm) colors representing anticyclonic (cyclonic) vorticity. Red lines show the 500 mb heights.

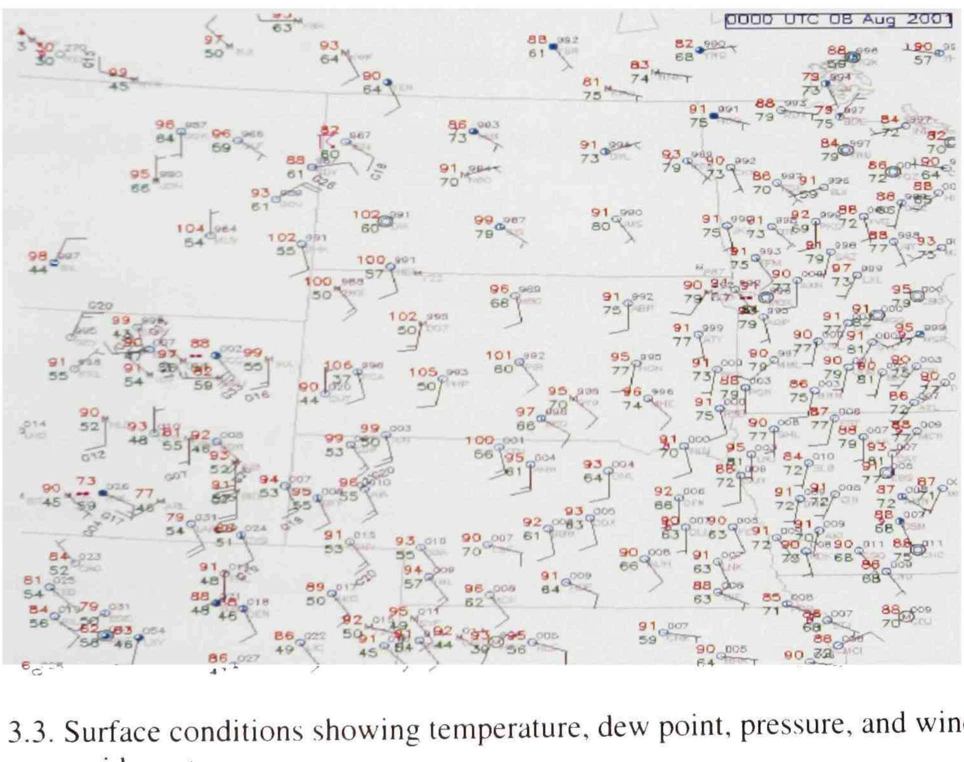

Figure 3.3. Surface conditions showing temperature, dew point, pressure, and wind speed in the upper mid-west.

formed it appeared to travel coincident to the moisture supply, as 700 and 850 mb mixing ratios exceeded 8 g/kg and 16 g/kg, respectively. As expected with very warm temperatures and high moisture content, θ_e values were enormously high with values over 375 K near the surface and 365 K at 850 mb (Figure 3.4). The 0Z ETA shows a very weak southerly LLJ over western South Dakota (SD) at 0Z with wind magnitudes ranging between 5 and 10 m/s (Figure 3.5). However by 6Z, the time of derecho initiation, no LLJ exists. This differs from Johns (1993) conceptual model for bow echo development, which shows the LLJ as an integral part of bow echo development. θ_e overrunning was still present at 700 and 850 mb during derecho initiation as well as the weak upper-level short wave. By 12Z the derecho traveled into western portions of the upper peninsula of MI. The upper-level short wave was still present at 700 and 500 mb, along with WAA at 700 and 850mb. Again, no LLJ could be found. Winds as this point were unidirectional out of the west from 850 mb up through the 200 mb level. Absence of a low-level jet would suggest convection was forming along the leading edge of the outflow.

The final severe wind report occurred in extreme eastern MI at 2140Z as the system moved into Ontario, here the derecho quickly fell apart. Forcing at the mid-and-upper-levels was almost non-existent as both 700 and 500mb short waves were positioned well north of the convection (Figure 3.6). Low-level and surface winds were out of the southwest; this compares with findings from Bentley et al. (2000) in the decay region for southeast-moving derechos. Another similarity to that of Bentley is a decrease in the horizontal θ_e gradient, as values plummeted nearly 20 K over approximately 100

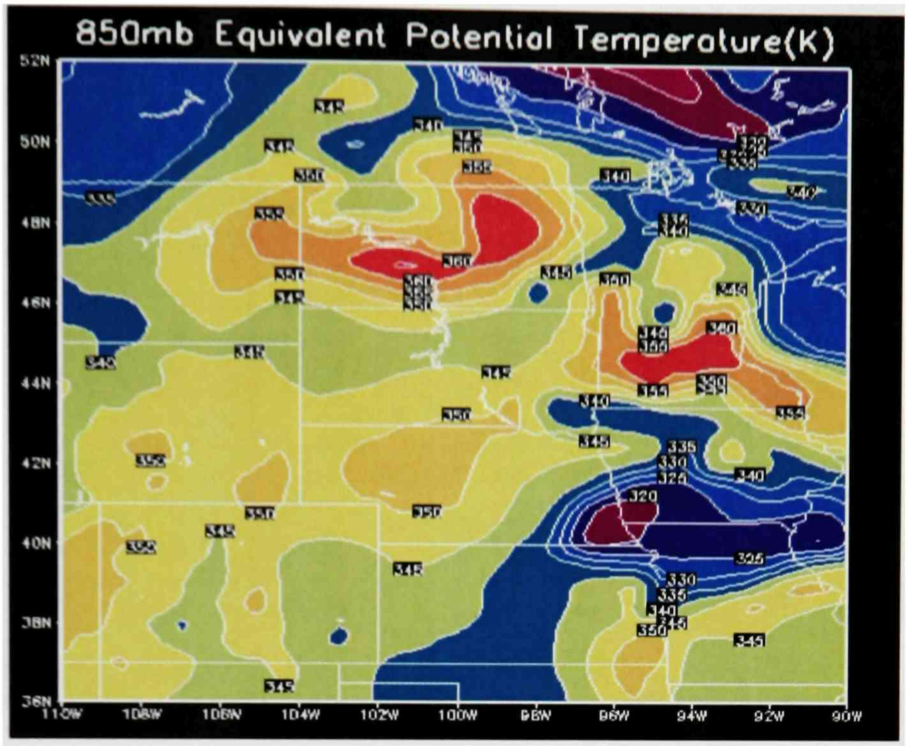

Figure 3.4. 0Z 8 August 2001. Depicts extremely high θ_e values 850 mb.

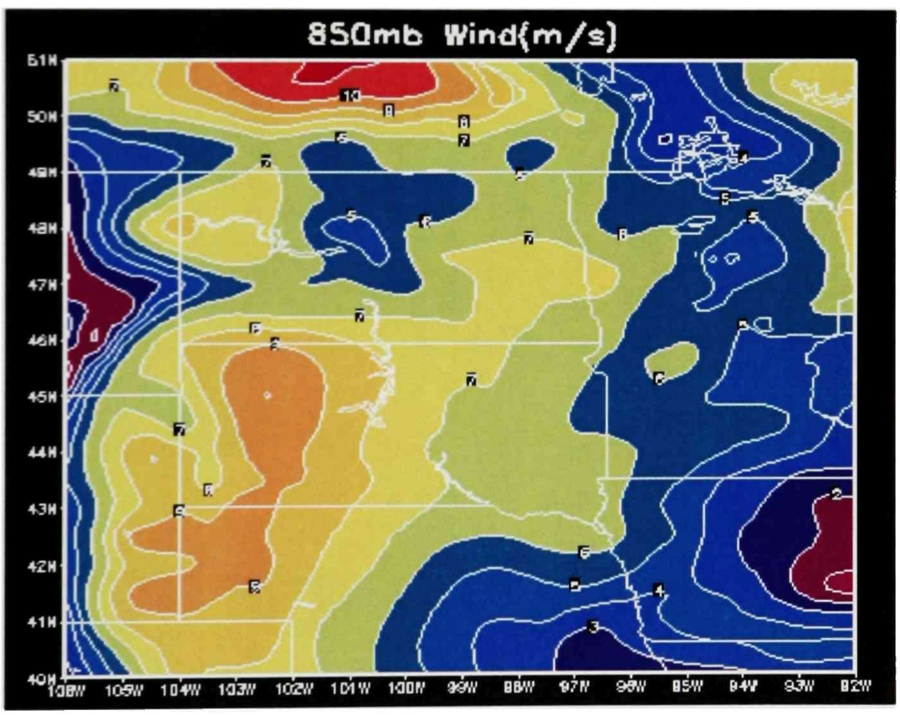

Figure 3.5. 0Z 8 August 2001. Shows a relatively weak LLJ at 850 mb.

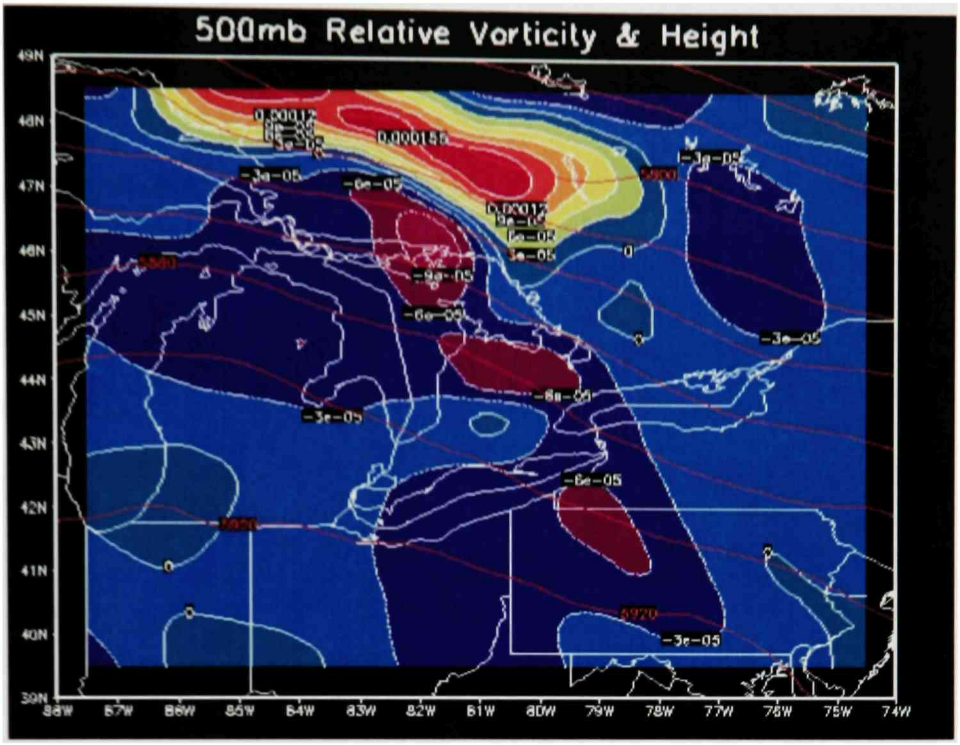

Figure 3.6. Same as Figure 3.2, except analysis at 0Z 9 August 2001.

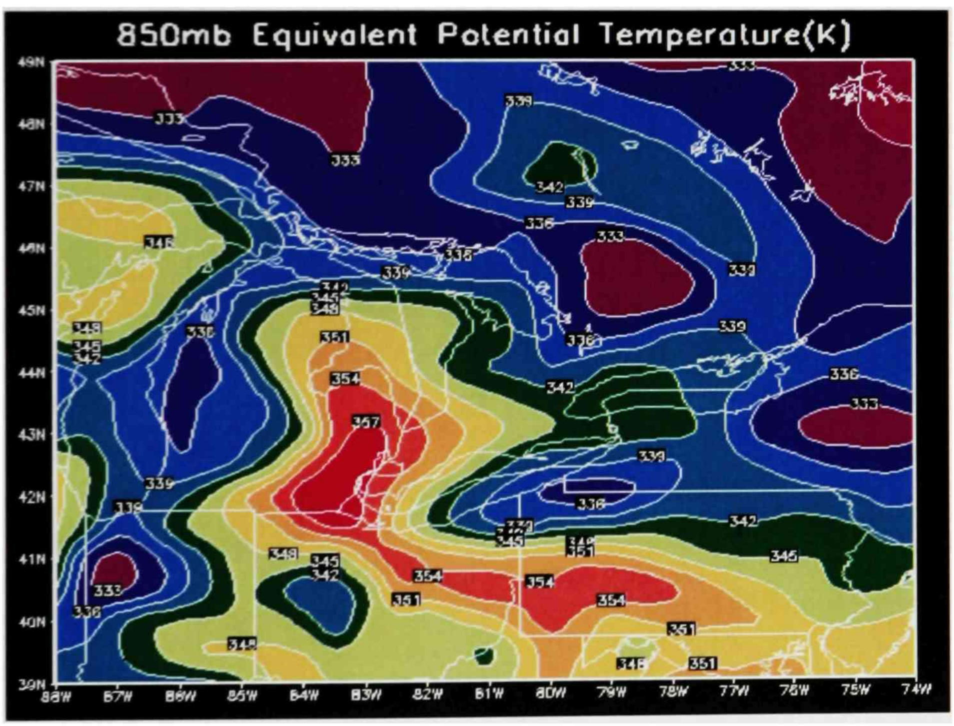

Figure 3.7. ETA analysis at 0Z 9 August 2001.

km, ranging from 335 K to 355 K at 850 mb (Figure 3.7). The lower θ_e values were directly due to the decrease in moisture in the low levels. The 850 mb mixing ratio dropped 5 g/kg over the same 100 km extent (Figure 3.8). Convective inhibition, which was nonexistent over the lifetime of the derecho, became evident in the decay region as CIN values jumped to 100-300 J/kg. The most noticeable factor for the demise of the system was the lack of moisture.

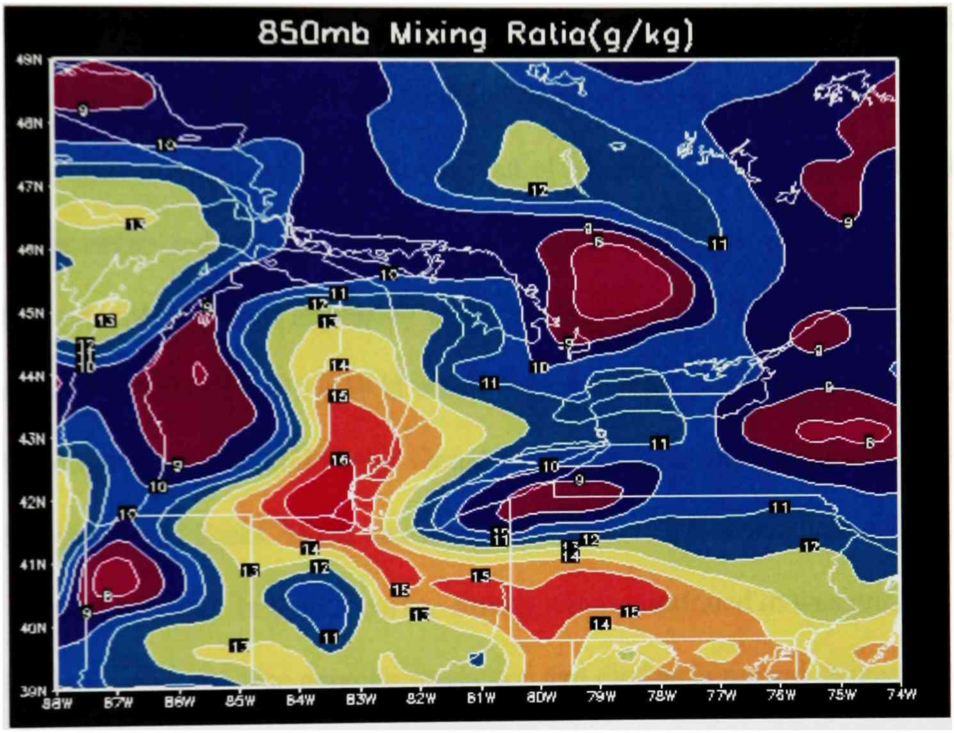

Figure 3.8. ETA analysis at 0Z 9 August 2001.

Case II

Synopsis

The derecho on 8-9 August 2001 began in north-central ND. The derecho formed less than 24 hours after the Case I derecho. This is expected as 60% of warm season derechos are followed by a second event the following day (Bentley & Sparks, 2003), while derecho families with 3 or more events occurring 33% of the time. Radar imagery shows initial convection formed over extreme southeast Saskatchewan (SK) almost nine hours before initiation of the derecho. Relatively benign convection began as a widespread multi-cellular complex. Moving out of SK into ND the complex slowly became more organized. As the system moved though central portions of ND a line of storms formed with segments appearing supercellular in nature. The first severe report occurred shortly thereafter with a 58 kt wind. Severe reports increased as the derecho traveled through eastern ND into MN. Grand Forks Air Force base measured a 99 kt wind while the Grand Forks ASOS measured at 88 kt wind. As a result an estimated $11 million damage occurred in Grand Forks. Strong winds continued in western MN with a 69 kt wind at Crookston. The derecho weakened and died as is moved through the arrowhead of MN.

This was a hybrid-type of derecho, as denoted by Doswell and Evans (2001). At first the radar pattern was consistent with that of a type I reflectivity but morphed into a pattern that did not fit into any pattern type in its latter stages. This was the shortest derecho sampled, lasting just over seven hours with only 21 severe reports of wind (Figure 3.9). Again, the low number of reports is likely due the sparsity of population. Although the system was short lived and had few wind reports, the two strongest reports occurred with this derecho when comparing the four events. This may be in part to a high translation speed of 52 kt as it covered 700 km.

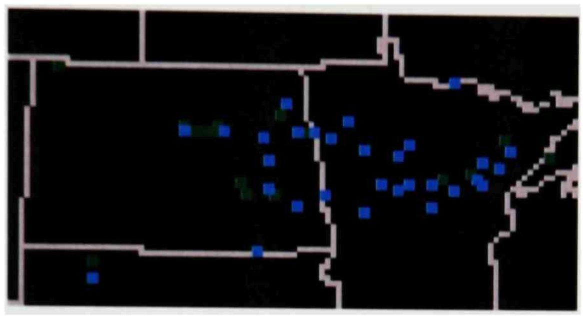

Figure 3.9. Severe wind damage or wind gusts of 50 kt or greater during Case II.

Environment

The 12Z ETA analysis of surface observations showed a surface low over western ND. Convection began in southeast SK along a cold front and just ahead of an upper-level short-wave trough. The right rear of the upper-level jet was also impinging on the area. Convection began with a few individual cells but as the cold front moved southeast development started to expand. Initially, surface analysis showed relatively stable conditions with low CAPE values and high CINs. Therefore the first convection formed exclusively from synoptic-scale forcing.

By mid-afternoon the storms moved into a highly unstable atmosphere with severe reports shortly following. Lifted indices were below –9 (Figure 3.10) with CAPE values over 4000 J/kg (Figure 3.11). The right rear quadrant of the upper-level jet was placed over ND as a relatively strong 500 mb short wave dropped across the northern part

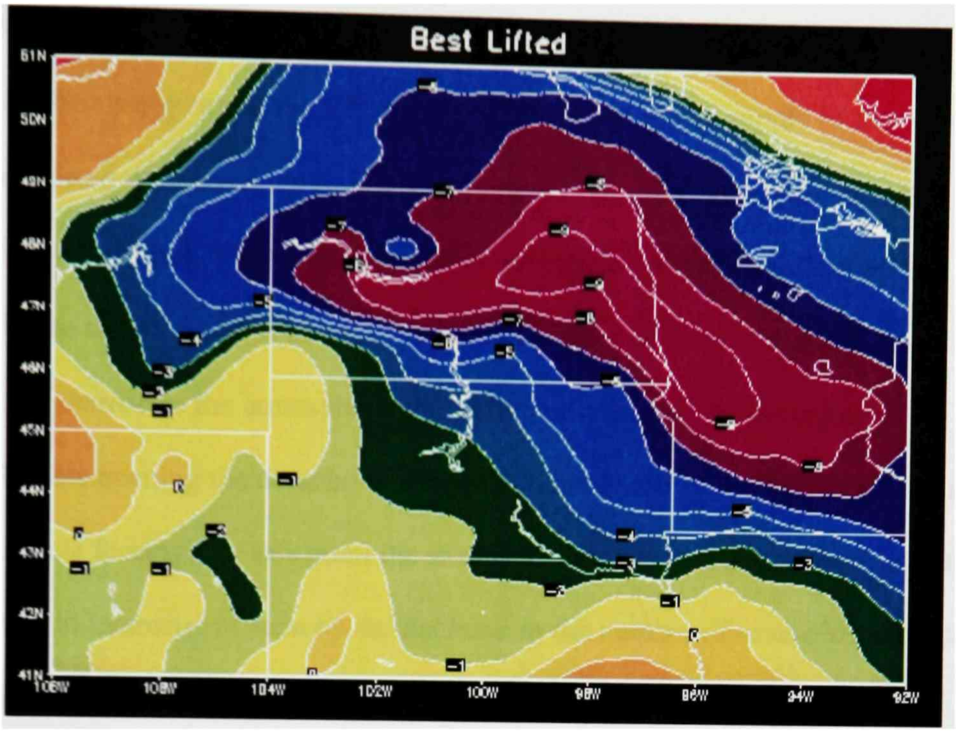

Figure 3.10. Lifted index at 21Z 8 August 2001.

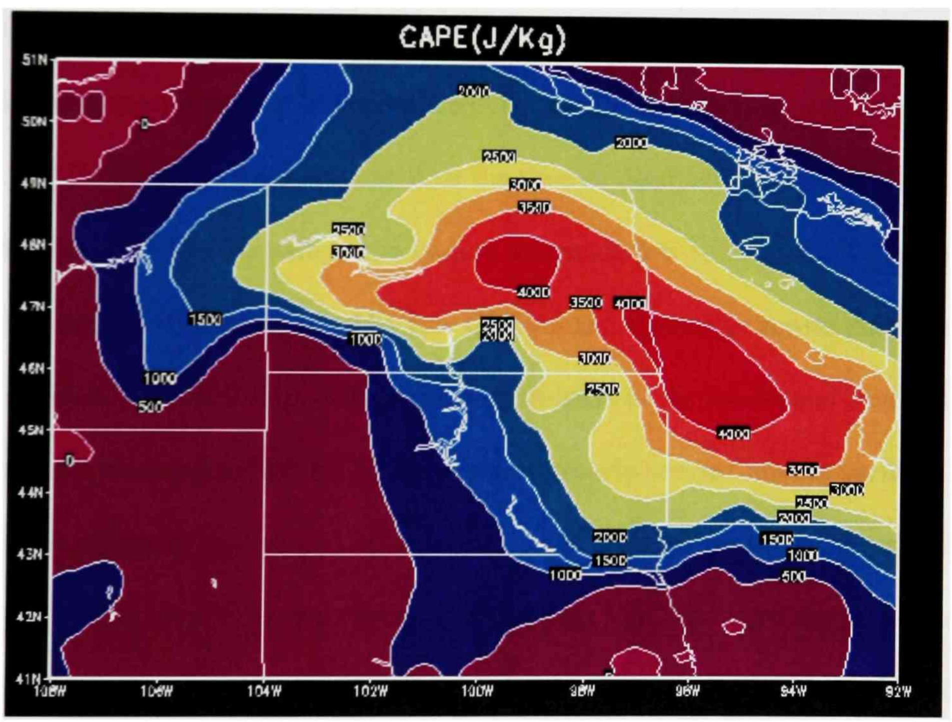

Figure 3.11. Surface based CAPE at 21Z 8 August 2001.

of the state. The cold front continued to move southeast across eastern ND with convection becoming organized along the boundary. An ample supply of low-level moisture existed with widespread 70 F dewpoints (Figure 3.12) and mixing ratios of 14 g/kg at 850 mb (Figure 3.13). No convective inhibition was present allowing for convection to thrive. Storms tried to fire along the front as far south as southwest SD but met a quick demise as the atmosphere was sufficiently capped in this region.

By late evening the derecho had raced 200 km ahead of the cold front and all synoptic-scale forcing. At this point the storms had moved into eastern MN and started to diminish in intensity, as seen by the decrease in the number of severe wind reports. With no synoptic forcing, storms existed strictly due to forcing along the outflow boundary. After analyzing model data, it appeared there to be little reason for the derecho to dissipate, other than loss of synoptic forcing and the LLJ. With very high instability parameters the loss of synoptic forcing would not likely lead to derecho demise. CAPE values at 6Z 9 August, near the time of dissipation, were still ranging from 2000-4000 J/kg in the path of the system alongside low lifted indices. The high instabilities were also accompanied by low CIN values, especially across northeastern MN with values below 50 J/kg. After further evaluation of the model and actual surface observations it was noticed the ETA analysis was grossly overestimating surface temperatures depicting low to mid 80's (Figure 3.14) and dew points in the low to mid 70's (Figure 3.15). Earlier in the afternoon a compact MSC moved through northeastern MN, which may be the reason why the 6Z ETA analysis shows inflated CAPE and lifted indices, as surface moisture and temperature play large rolls in computation of these

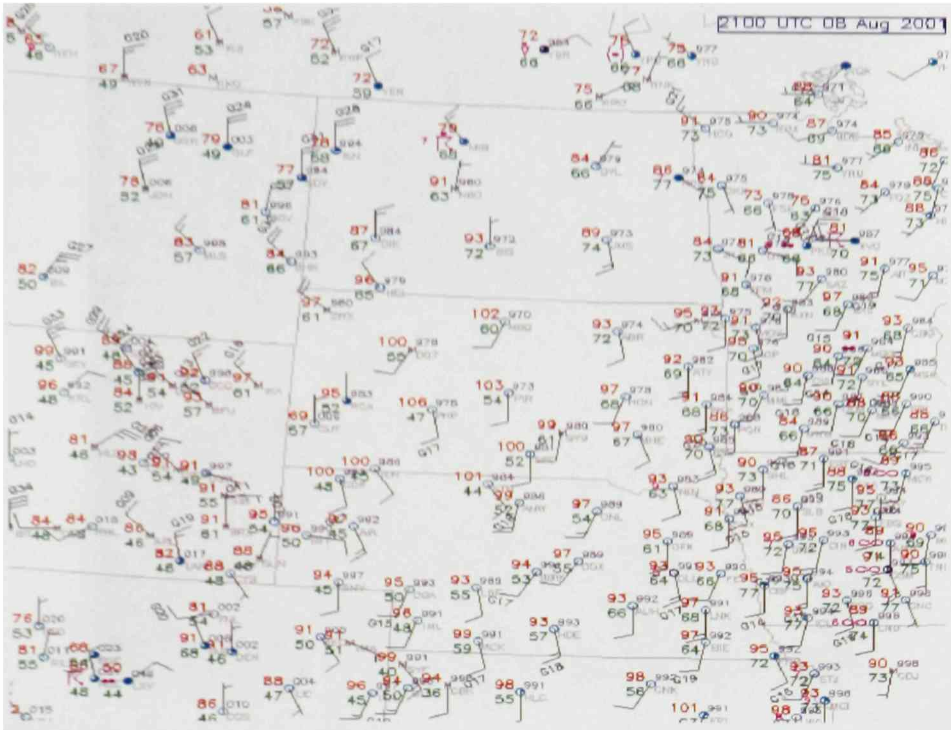

Figure 3.12. Surface analysis at 21Z 8 August 2001.

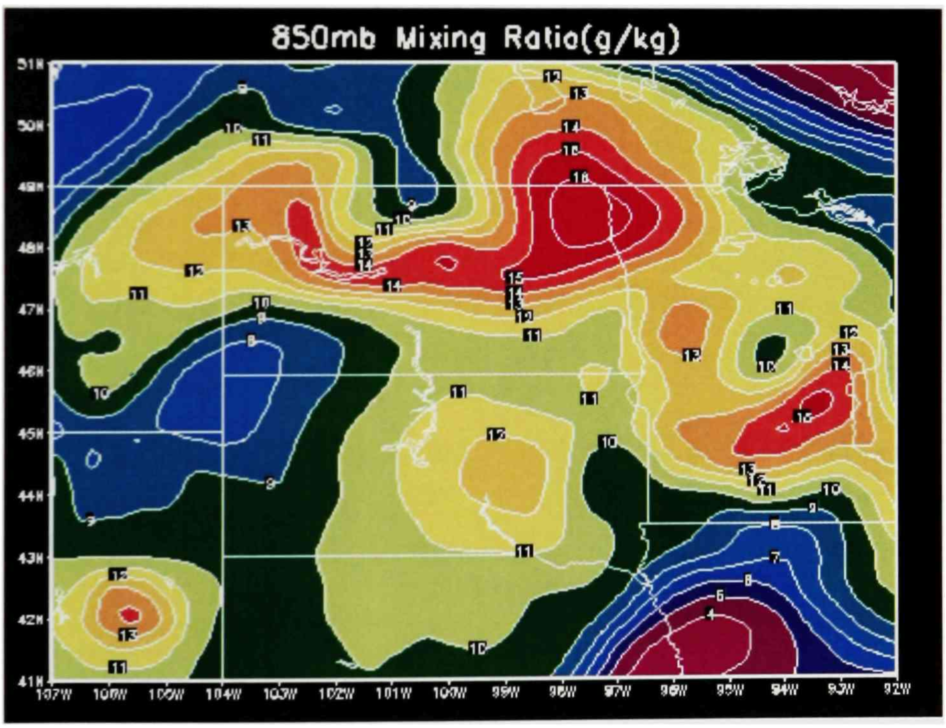

Figure 3.13. Mixing ratio in grams per kilogram at 21Z 8 August 2001.

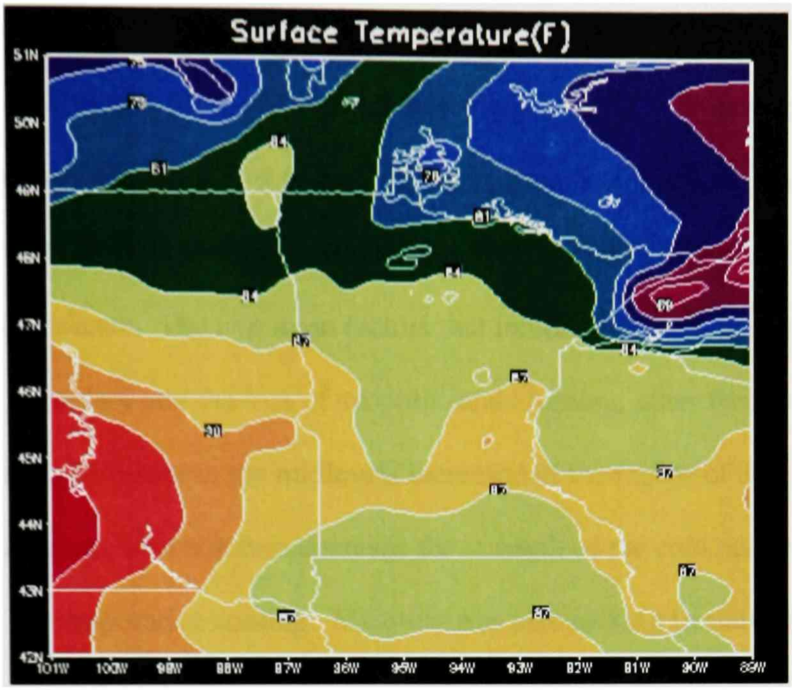

Figure 3.14. ETA analysis of surface temperatures at 6Z 9 August 2001. Compare with actual surface observations in figure 3.16.

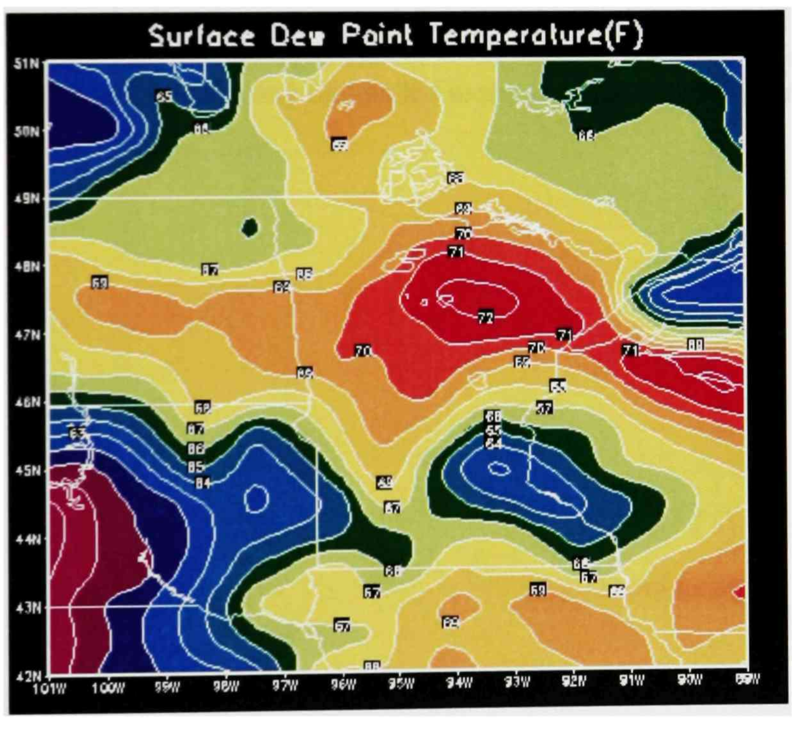

Figure 3.15. Same as Figure 3.14, except for dew points. Again compare with Figure 3.16.

parameters. ETA analysis likely did not pick up on this storm complex as it cooled the boundary layer. This is evident as surface temperatures ahead of the derecho were in the mid 60's in eastern MN, while low to mid 70's were prevalent in the regions not affected by the earlier storm system (Figure 3.16). Also, CIN values would be much lower then the ETA would indicate. The two main factors that inhibited the derecho were likely the cooling of the boundary and the loss of synoptic-scale forcing; other factors may have also played a roll. Moisture in the midlevels increased in the region of decay leading to a decrease in buoyancy, which in turn decrease the strength of the cold pool as less dry air was available for evaporative cooling. Moisture was also lacking in southern MN as a relatively large region of dry air existed from just above the surface in the low levels. This favored derecho dissipation, especially as the low-level jet (LLJ) was the main source of moisture to the DMSC early in its lifecycle. At this point the LLJ was nearly nonexistent. It is apparent that many factors led to the termination of this derecho.

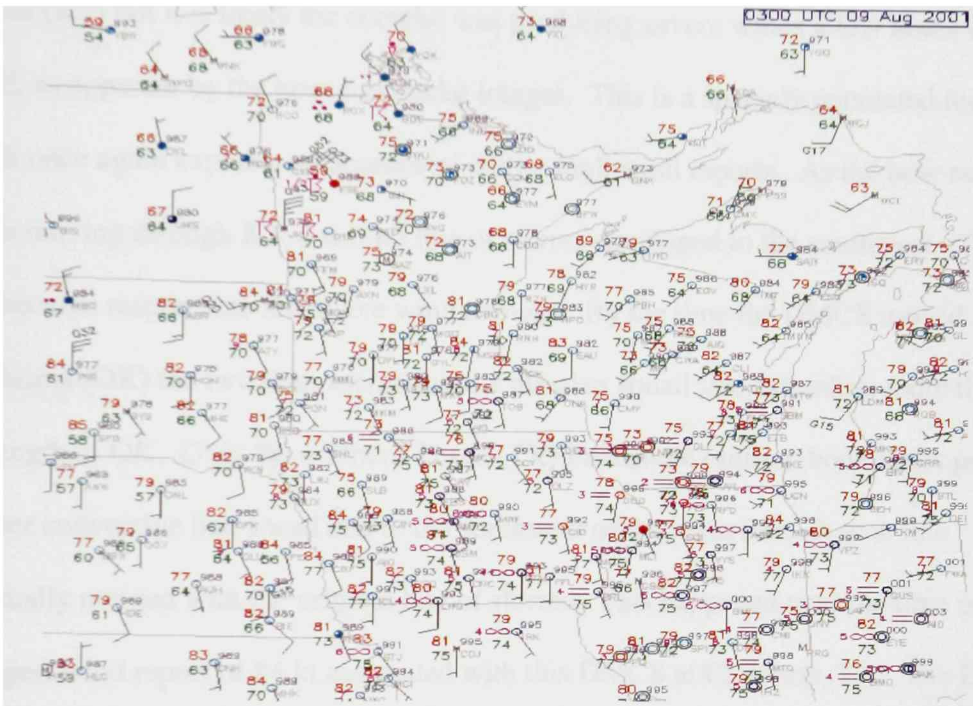

Figure 3.16. Surface analysis at 3Z 9 August 2001. AT 3Z temperatures and dew points are already significantly lower then ETA values indicate at 6Z. 6Z surface analysis was not available.

Case III

Synopsis

First of signs of convection with the 15-16 June 2001 derecho were evident over northwest Nebraska at 09Z. The region of convection began to proliferate while propagating southeast. At 1835Z the first severe wind report was recorded in northwest Kansas (KS) but it is likely the derecho was producing severe winds a few hours earlier in NE, as apparent by the bow echo radar images. This is a sparsely populated region, which once again explains an absence of earlier high wind reports. As the bow echo began moving through KS, a second line of storms developed to the southwest. This line also became responsible for severe wind damage. By the time the DMCS moved into Oklahoma (OK) the two lines merged into a massive squall line extending more then half the length of OK. Over the northern Texas (TX) Panhandle outflow boundaries produced another convective line ahead and to the southwest of the main line. A new line eventually merged with the original line of storms. This happened near the time of strongest wind report of 84 kt associated with this DMCS at Childress, TX. The DMCS continued southeast across TX before moving into the Gulf of Mexico. The intense convection persisted a few more hours before weakening and dying completely.

The derecho had characteristics of a progressive derecho, and its radar pattern suggested that is was of a Type I as there were multiple bowing segments over the extent of the squall line. This was another long-lived derecho (17 hours) with the last wind report at 1130Z on 16 June. There were 153 wind reports (Figure 3.17) over the lifetime of this system with a major axis over 1100 km. This gives an average forward propagation speed of 35 kt, which was much slower then the 45 kt average for progressive derechos (Johns & Hirt, 1987).

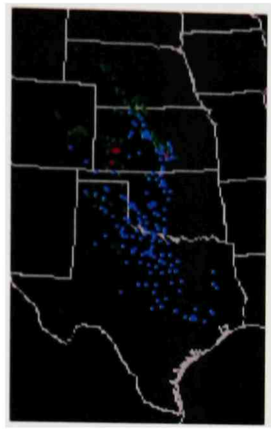

Figure 3.17. Severe wind gusts or wind damage during case III.

Environment

An upper-level ridge dominated the western U.S. with a trough in the east, placing the region of derecho initiation in northwest flow (Figure 3.18). Two branches of the upper-level jet existed with the northern branch diving through ND and MN into the southeast U.S (Figure 3.19), while the other branch extended across the southern U.S. Western NE had CAPE values upwards of 1200 J/kg with a lifted index of –4, however, a fairly strong cap existed with CIN values ranging between 50-200 J/kg (Figure 3.20). Convection began on the northern and eastern periphery of the most unstable air as denoted by the aforementioned CAPE and lifted values. A strong LLJ (Figure 3.21) was present in the region of convection formation with a 15 m/s flow. This was one of the triggering mechanisms in the development of the first storms. The LLJ also brought moisture in the region with a moist tongue stretching from southern Texas into

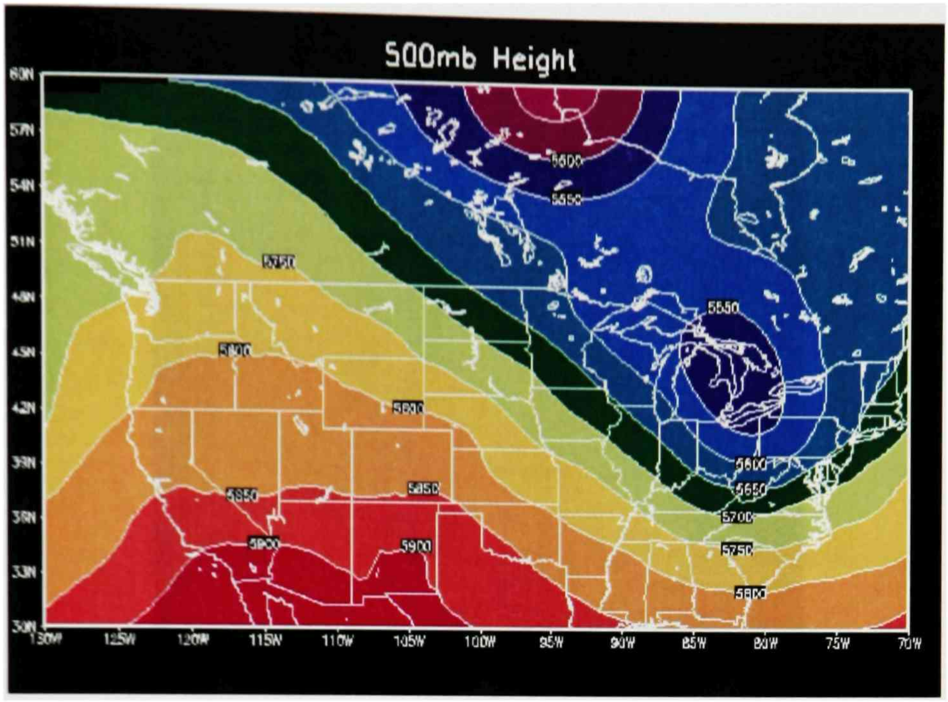

Figure 3.18. 500 mb geopotential height field 15Z 15 June 2002. Heights are shown in meters.

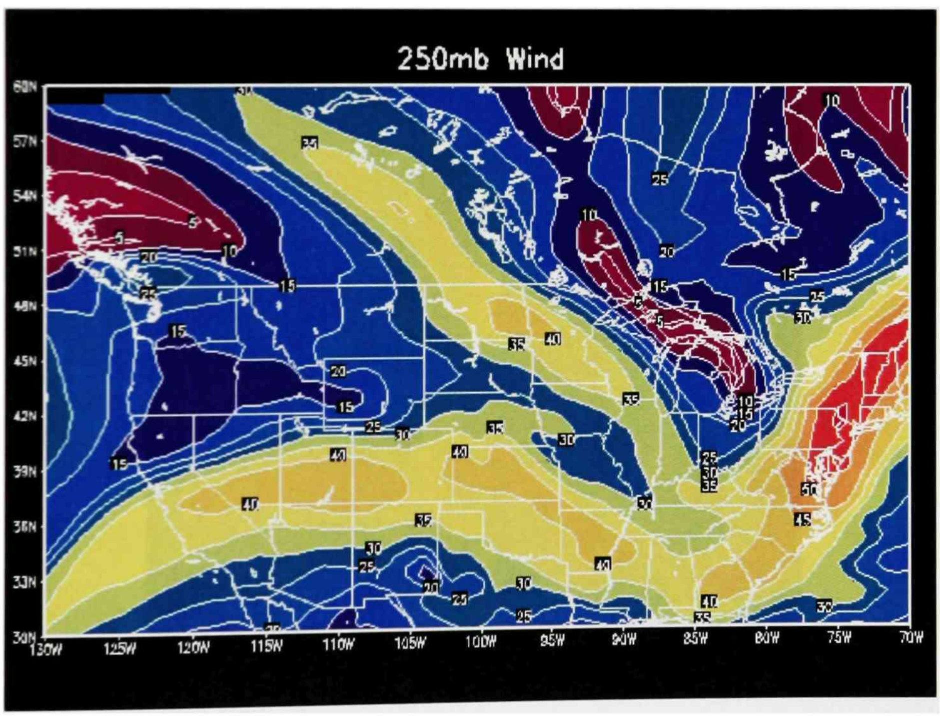

Figure 3.19. Shows upper-level jet stream at 15Z 15 June 2002 with wind speeds in m/s.

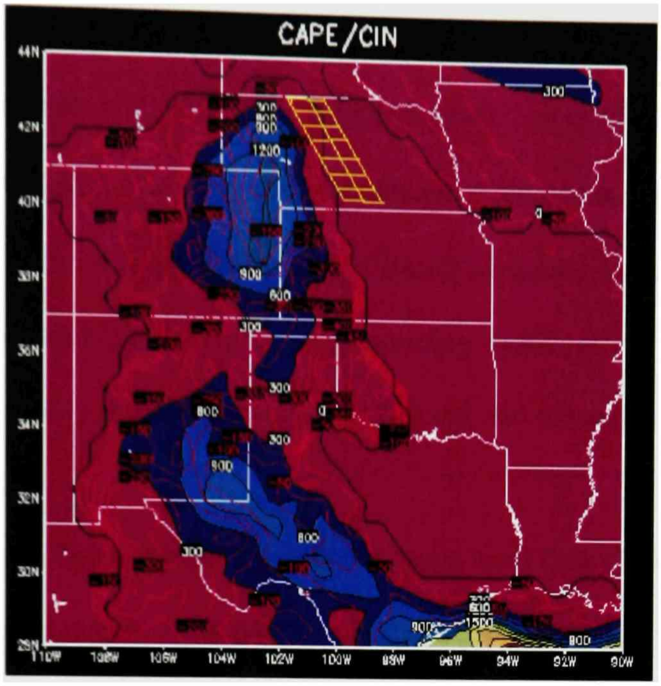

Figure 3.20 CAPE and CIN values in J/Kg at 15Z 15 June 2002. Red lines represent CIN values. The yellow parallelogram shows where the initial convection formed, notice it was to the east of the unstable air.

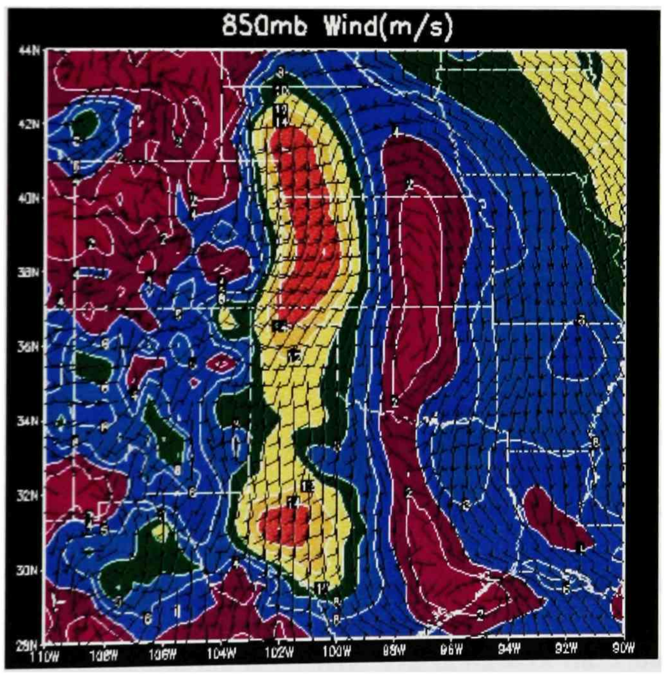

Figure 3.21. Contoured wind speeds overlaid with wind barbs at 15Z 15 June 2002. Depicts the LLJ and warm air advection over western NE.

eastern New Mexico and Colorado. A sharp moisture and temperature gradient was also present in the lower levels with 850 mb θ_e and mixing ratio values of 320 K and 6 g/kg, respectively, in northwest NE while northeast Colorado (CO) had θ_e values of 335 K and mixing ratios of 12 g/kg. It is quite obvious that strong isentropic forcing was occurring at 850 mb and is also visible at 700 mb, notwithstanding weaker at 700 mb. There also is a short wave embedded in the northwest flow at 700 and 500 mb aiding in synoptic forcing (Figure 3.22).

The derecho at first followed the mid-and upper-level flow (200-500 mb) but once convection moved into eastern NE it met a rapid demise with little moisture present. There was a lack of moisture in eastern NE (Figure 3.23), as mixing ratios were dropping rapidly here. By 0Z 16 June, convection was starting to form southward as outflows triggered new cell development in moist unstable air. ETA analysis showed ample moisture with 850 mb mixing ratios ranging from 9 to 13 g/kg. CAPE values hovered around 1200 with a lifted index of –7. Synoptic forcing was still evident with θ_e overrunning in the lower levels and a short wave at 700 and 500 mb continuing to trail the main line of convection. An upper-level jet max at 250 mb was also present helping to enhance lift.

The DMCS continued across TX generally following the mid-and upper-level wind pattern, which was also coincident to the deepest moisture. Conditions remained similar throughout much of the system's life as unstable air, deep moisture, θ_e overrunning, and upper-level forcing persisted. The demise of the system occurred over the Gulf of Mexico south of Louisiana. Synoptic conditions remained favorable for the continuation of the DMCS except the deep moisture present earlier subsided. This likely led to the demise of the system as convective updrafts could no longer be sustained. Also, CIN values indicated an extremely strong cap indicative of a very stable air in the region of demise ranging from 300 to 400 J/kg.

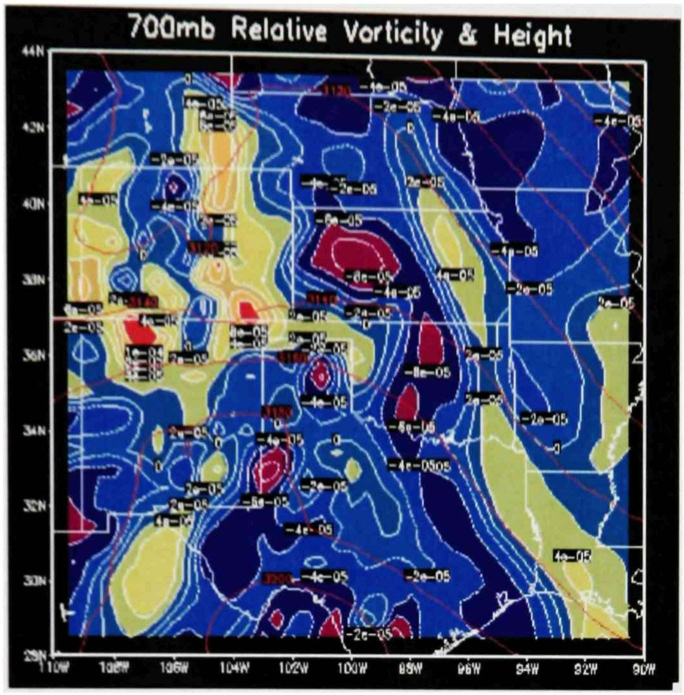

Figure 3.22 Depicts relative vorticity advection at 18Z 15 August 2001.

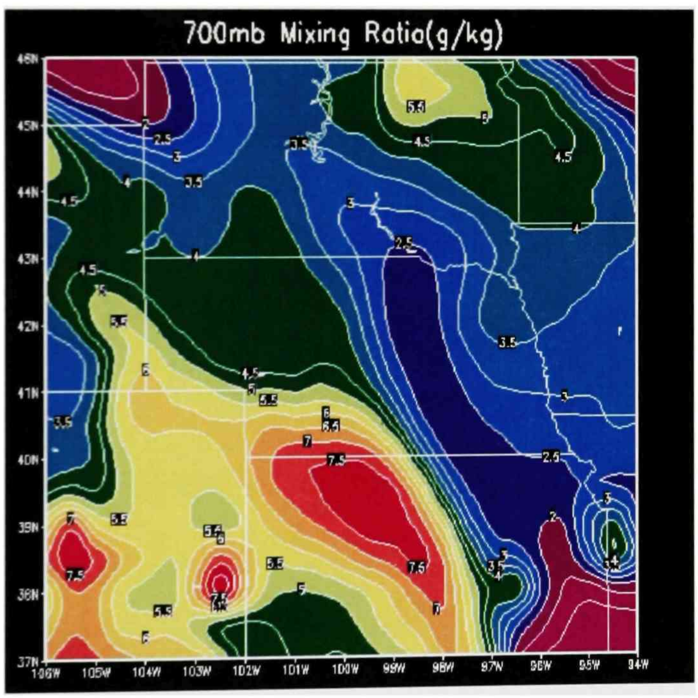

Figure 3.23. Mixing ratio at 18Z 15 June 2002. Shows the lack of moisture in eastern NE. Storms died quickly once moving into this region, however, convection continued to build south and west into the deeper moisture.

Case IV

Synopsis

First signs of convection from which the derecho developed occur at 18Z 26 August 2002 in northeast NE. However, the likely trigger for this convection was due to outflow from storms moving through central NE earlier that morning. The central NE storms gained their roots from storms originating on the lee slopes in Montana nearly 24 hrs earlier! One of these storms turned right as is passed into ND, traveling southward. This storm continued south into SD and eventually into central NE producing an outflow. It is very likely that this derecho would have never formed had this one single supercell not persisted from central MT into central NE. This derecho began in the early afternoon with the first severe wind report at 2000Z in extreme southwest NE. Movement was southeast passing through KS, OK, TX and finally western LA before dying in the Gulf of Mexico. Convection developed rapidly as a small cluster of storms exploded between 1830Z and 1930Z. The cluster quickly evolved into a single bowing line, almost immediately producing severe winds; as by 2010Z a 76 kt wind was recorded. Six tornadoes were reported in the first 90 minutes but relinquished as the line began to bow. The system continued to organized into an intense line of echoes as it moved into northwest KS. Convection remained organized producing numerous wind reports throughout the life of the derecho.

This very long-lived derecho lasted just shy of 25 hours and covered some 900 km. It was a good example of a Type I progressive derecho with multiple bowing segments along a well defined leading edge. There were 145 severe wind reports (Figure 3.24), of which 13 were over 65 kt.

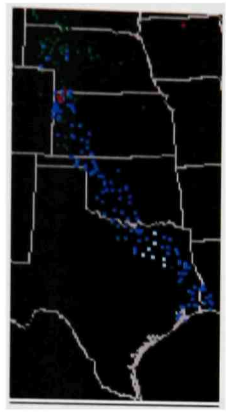

Figure 3.24 Severe wind gusts or wind damage during case IV.

Environment

Surface analysis depicts low 60's for dewpoint temperatures in the genesis region. A broad area of surface low pressure existed from ND through CO (Figure 3.25). The low-level jet is evident at 850 mb extending into southwest SD with 15 m/s winds at the jet core. The atmosphere was very unstable with lifted indices of –7 and CAPE values of 3000 J/kg. The 500 mb flow was westerly at 14 m/s, which is usually a bit weak for bow echo development. However, Johns and Hirt (1987) noted bow echo development might still occur with 500.mb winds of 13 to 18 m/s considering conditions are highly unstable. The upper-level jet was impinging on the region, as was a 500 mb short wave. Deep moisture was once again present during the onset of convection with mixing ratios of 8 and 13 g/kg at 700 and 850 mb, respectively (Figure 3.26).

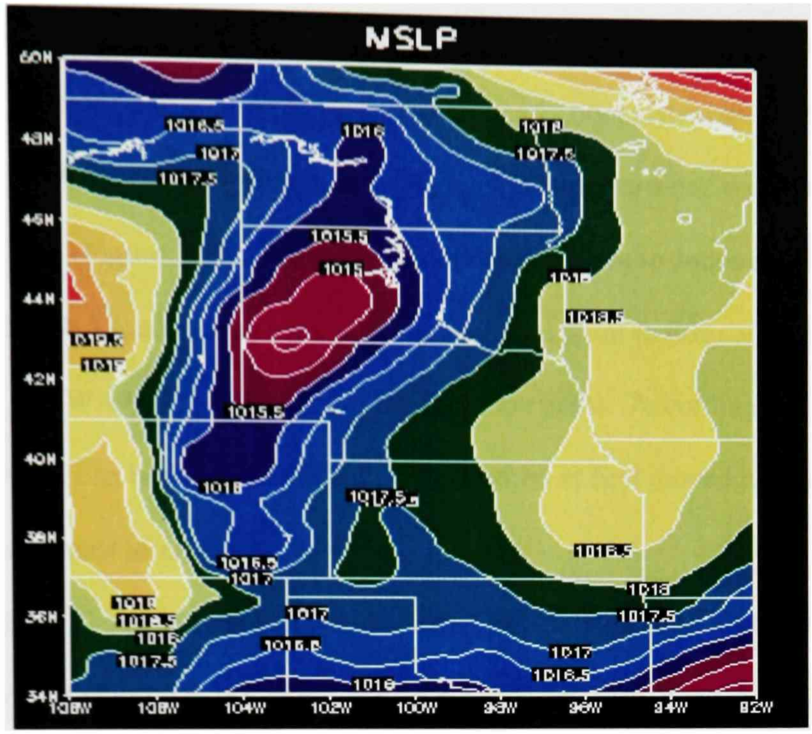

Figure 2.25 Surface pressure in mb at 12Z 26 August 2002.

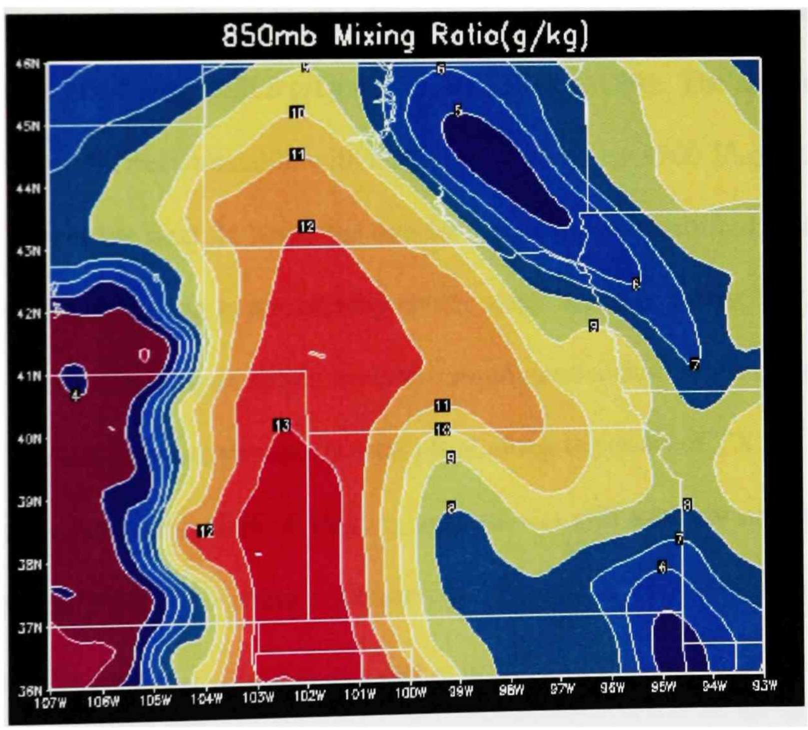

Figure 3.26. Mixing ratio at 12Z 26 August 2002.

This derecho initiated just ahead of the 500 mb short-wave trough as is pulled into western KS. Advection of isentropic surfaces was nearly nonexistent as very weak warm air advection (WAA) was occurring at 700 mb, while neutral to weak cold air advection (CAA) at 850 mb (Figure 3.27). This is in direct disagreement to Johns and Hirt (1987). They found that WAA advection present at the initiation point in 86% of cases studied, and all cases had WAA within 320 km of the initiation point. According to ETA model analysis no WAA can be found at 850 mb. The derecho at first moved just east of south following the deepest moisture.

By 0Z on 27 August the surface low over CO had filled with a new low forming over New Mexico (Figure 3.28). High pressure dominated the Central Plains; this allowed Gulf of Mexico moisture to be pumped into the derecho as it propagated southeast. This moisture allowed for the derecho to sustain itself. Analysis showed 850 mb mixing ratios of 14 g/kg with 8 g/kg at 700 mb (Figure 3.29). The air directly ahead of the system was still very unstable with CAPE values of over 3500 J/kg and lifted indices of –8. Over the next 21 hours the overall synoptic pattern shifted east with the derecho environment staying in a relatively steady state. In other words, the atmosphere remained very unstable with an ample moisture supply and a short wave directly behind the DMSC. The last convective reports took place along the coast of TX but strong convection endured into the Gulf of Mexico, as there was still a steady supply of moisture. Ironically the atmosphere dried out over the central Gulf leading to the demise of convection (Figure 3.30). Amazingly this is just shy of three days from when the first convection formed over eastern MT.

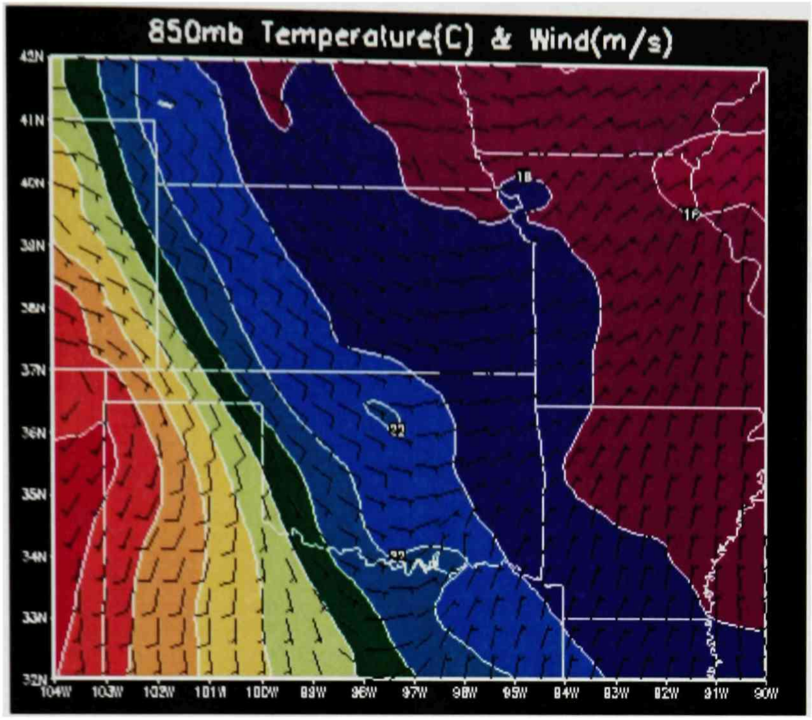

Figure 3.27. Equivalent potential temperature at 0Z 27August 2002 overlaid with barbs to show temperature advection. Notice only CAA in the genesis region (southwest NE).

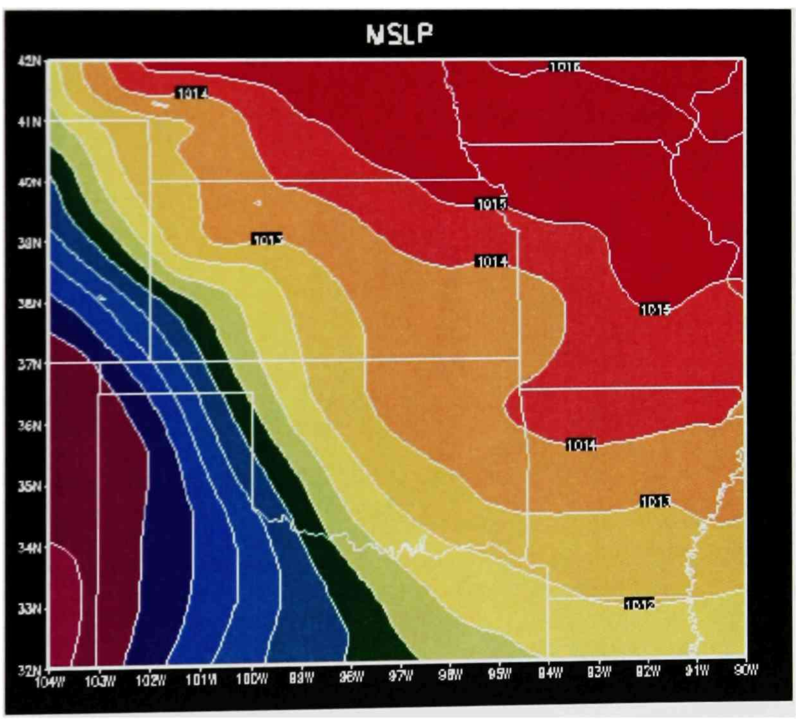

Figure 3.28. Surface pressure in mb at 0Z 27 August 2002.

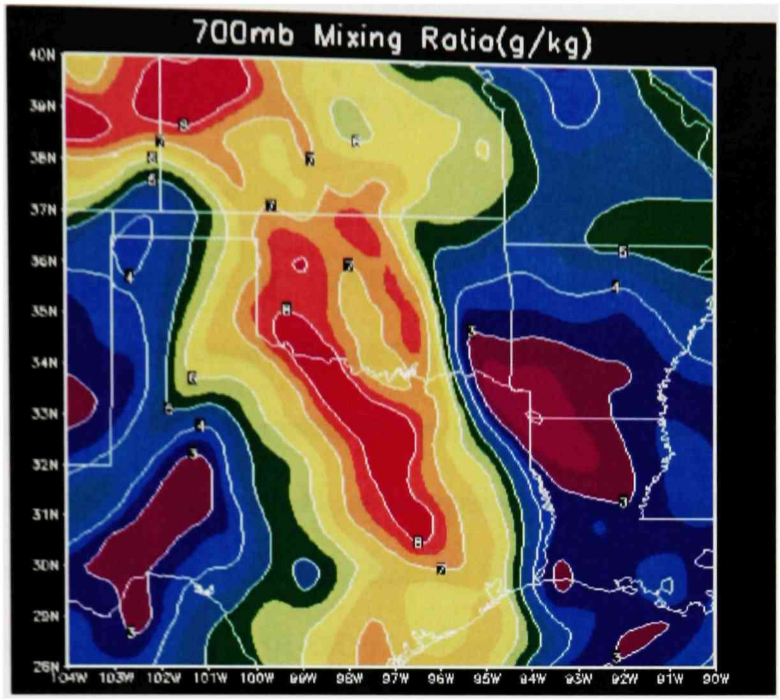

Figure 3.29. Mixing Ratio at 12Z 27 August 2002. The derecho followed the deepest moisture, where values were above 6 g/kg.

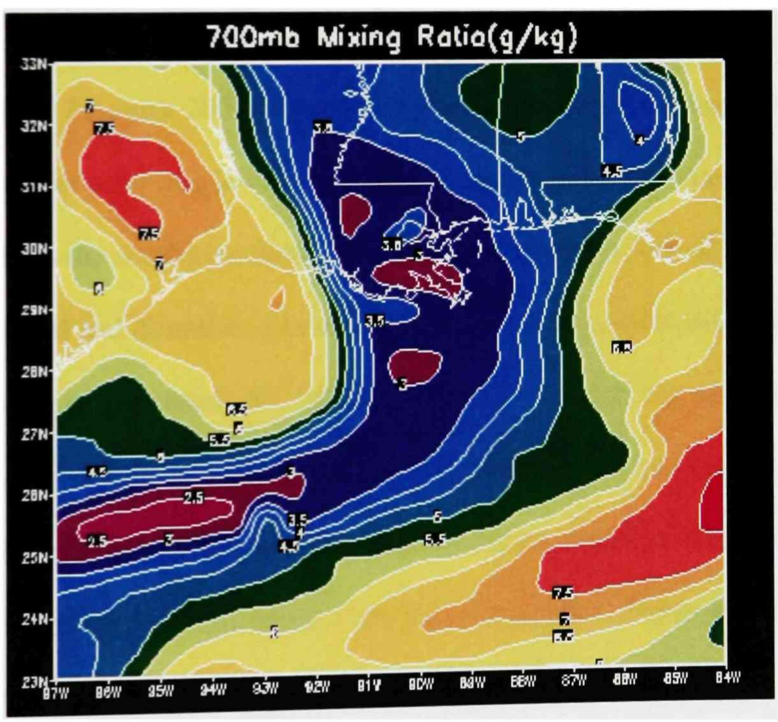

Figure 3.30. 700 mb mixing ratio at 0Z 28 August 2002.

CHAPTER IV

RADAR ANALYSIS

In this chapter, an overview of storm evolution involving the four case studies in chapter 3 will be completed using WSR-88D radar imagery. Also, a more detailed radar analysis is completed to determine what mechanism(s) are responsible in the creation of extreme wind events. To be classifed as an extreme wind event, a measured wind of at least 74 kt is needed. Data were obtained from the National Climate Data Center (NCDC) and viewed using the WSR-88D Algorithm Testing and Display System (WATADS), available from the National Severe Storms Laboratory (NSSL).

Case I

At 20Z on 7 August 2001, composite radar imagery shows a line of light convective showers occurring in western ND and eastern MT with a lone strong convective cell on the southwest flank. By 0Z on 8 August, the line of showers had expanded eastward and diminished in intensity, while on the southwest flank a small complex of strong cells existed. By 2Z the light showers had all but dissipated as a complex of strong storms became organized and continue to progress eastward. At that point convection was over a very sparsely populated area, which is likely the reason for the nonexistence of severe wind reports over the next 3 hours. Figure 4.1 shows the progression of the convection during this period. Severe wind reports were expected as convection was very intense as evident by radar reflectivity. The convection began to

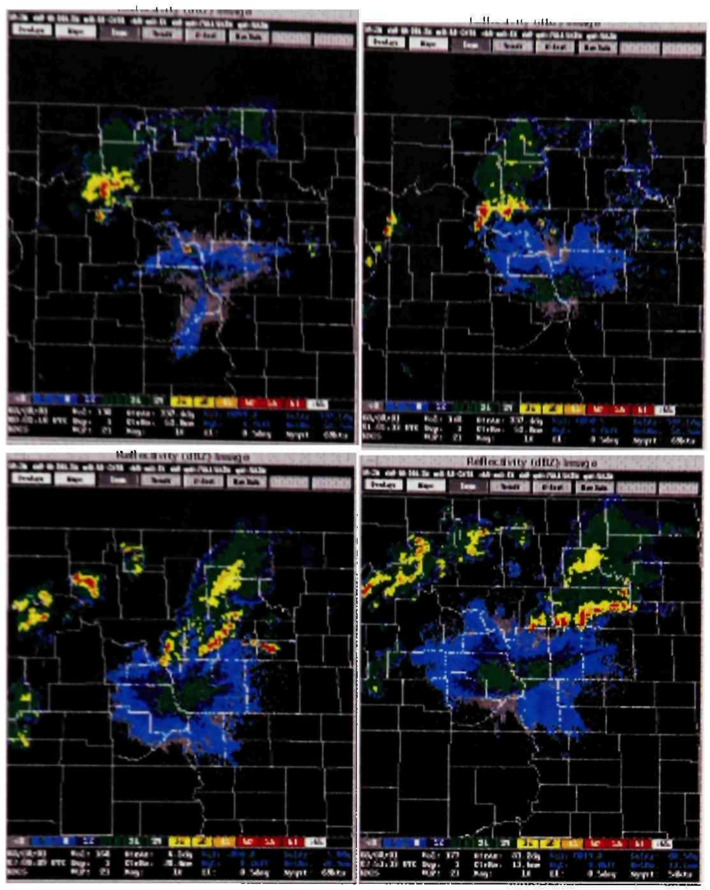

Figure 4.1. Evolution of convective complex in north central ND, prior to derecho initiation.

become linear by 5Z with three main convective regions within the squall line. By 6Z the line contracts into one large single convective element, which resembles an extremely large super cell (Figure 4.2). At this time severe wind reports began to occur with regular frequency as the system approaches a more densely populated area. Also in Figure 4.2, radar reflectivity shows no evidence of a rear inflow jet or bowing line echo wave pattern (LEWP). In many instances one or both of these features could be seen at the time of a severe wind reports. This suggests that another process may have been responsible in creating the high winds. Strong outflow or a convective downdraft such as a

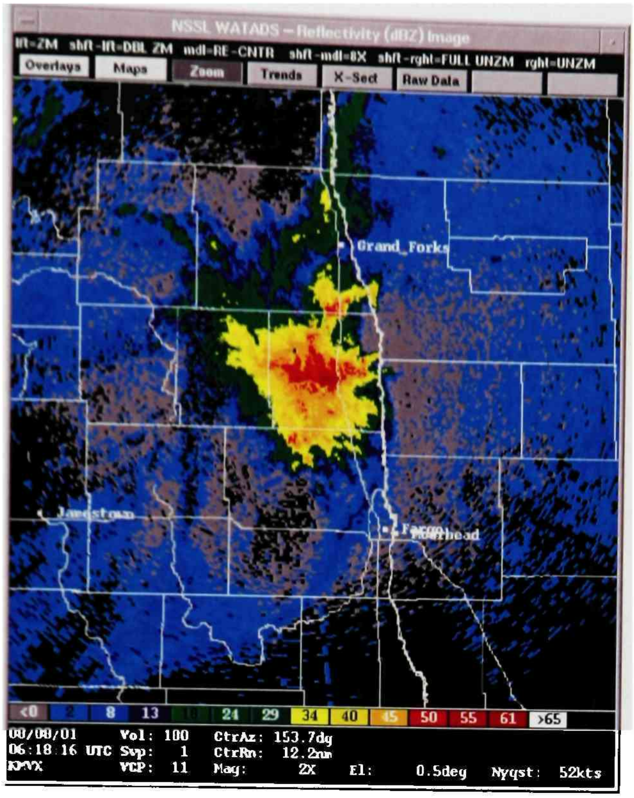

Figure 4.2. Radar reflectivity over eastern ND at 0618Z.

downburst/microburst are plausible explanations, however, radial velocity data suggested otherwise. The lowest tilt angle from the National Weather Service radar in Mayville, ND shows storm relative velocities of greater than 64 kt over an exceptionally large area (Figure 4.3). This would preclude high winds due to downdrafts. Also, the highest radial velocities existed well behind the gust front, which would exclude storm outflow along the gust front as a cause of the severe winds. However, the outflow was strong enough to produce severe winds as Fargo, ND, reported a 55 kt wind during gust front passage. It is highly probable a dynamic effect other then the aforementioned was accountable for these intense winds.

As previously discussed in Chapter 2, surfaced-based mesovortices may form and

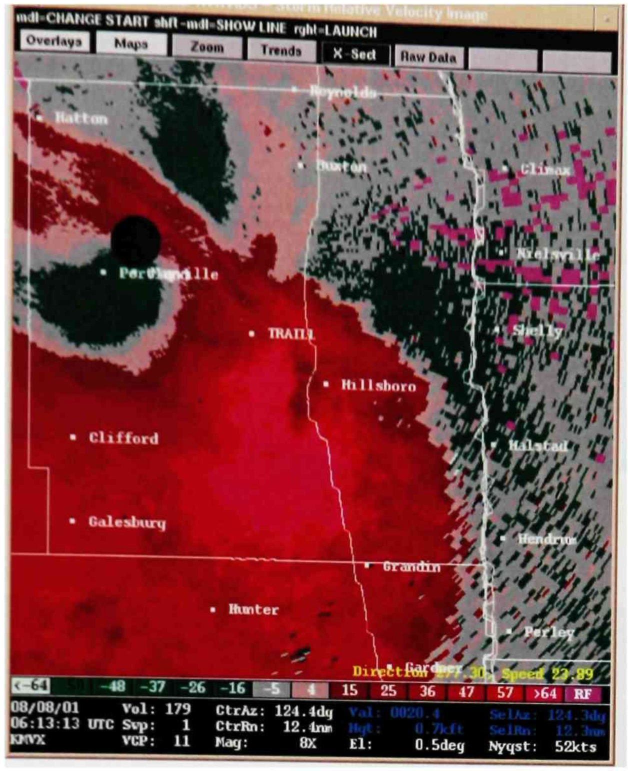

Figure 4.3. Storm relative radial velocities over eastern ND, at 0613Z.

create a baroclinic zone within a QLCS. Strong surface winds may form in response to the pressure difference generated by these mesovortices. Upon further examination, Mayville radar supports the existence of mesovortices along the northern end of the MCS (Figure 4.4). Vertical cross-sections show one large mesovortex near ground level at the time of the highest wind reports. Within the large vortex two smaller vortices are also evident. The large vortex was distinctly visible near the surface for over 30 minutes. This corresponds to the highest reported severe winds and the largest radial velocities.

A bow echo formed as the derecho moved through northwestern MN. As the derecho progressed across MN, into WI and MI, the bow echo continued to evolve. During this time, wind reports continued to be severe in nature and became more

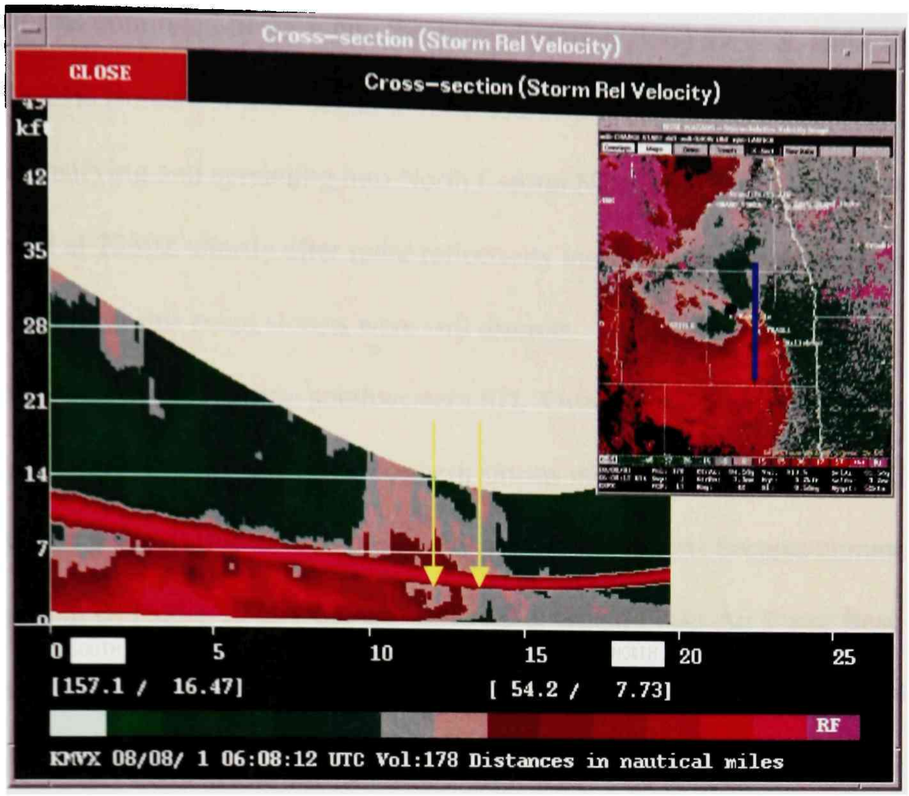

Figure 4.4. South to north vertical cross-section looking west. Superimposed image shows where cross section is taken as depicted by solid blue line. Yellow arrows point to mesovortices.

widespread, although the severity of the winds continued to remain low relative in comparison to the winds over eastern ND and western MN. This derecho did not produce a severe wind report over 56 kt from the point of bow echo formation in central MN to its demise over southeast MI.

Case II

Convection first began to form during morning hours of 8 August 2004, with the first signs occurring by 14Z. Development slowly increased throughout the morning with stronger isolated cells forming just north of the Canadian border in southwest SK by 17Z.

Isolated storms continued to form into the early afternoon along the U.S. and Canada border. By 21Z isolated storms began to form southward into western ND with coverage quickly intensifying and spreading into North Central ND. The first severe wind report was reported at 2230Z shortly after radar reflectivity indicated the development of stronger storms, at this point storms were still discrete. Isolated convective storms also fired along a line stretching into southwestern SD. Over the next two hours, storms in SD and south central ND died, while the northern storms moved into northeastern ND and started to form a squall line, as this occurred, severe wind reports became common. On the 9 August at 0115Z, a 99 kt wind was reported at Grand Forks Air Force Base as the squall line passed by. As in Case I there were some noticeable features or lack of expected features that may indicate the origin of the intense severe wind.

As in the previous case, there was no indication of WEN in proximity of the air base or anywhere along the entire length of the LEWP. Also similar to Case I, there was the lack of a discrete bowing LEWP or bowing line segment within the LEWP (Figure 4.5). Again, this suggests other factors may be responsible for the extremely strong wind. By 0041Z storm relative velocities at the lowest tilt once again indicated the existence of a mesovortex near the surface. Unfortunately this vortex was located 50 kilometers away from the Mayville Doppler radar; therefore, the lowest 2 kilometers of the atmosphere were not visible. At 0126Z the Grand Forks National Weather Service office reported an 88 kt wind with a 91 kt report at the Grand Forks airport. Radar imagery continues to show the existence of a mesovortex (Figure 4.6). Again the scan was too high to resolve the lowest 2 kilometers of the atmosphere, although, it is highly probable the lowest

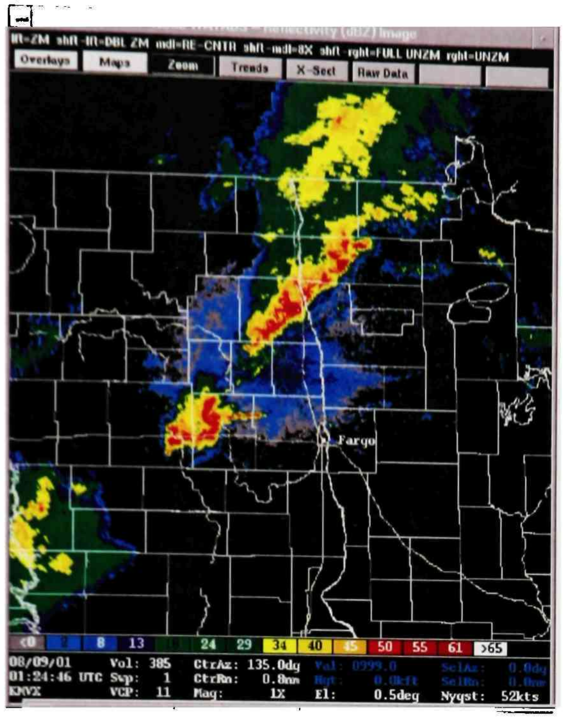

Figure 4.5. Doppler radar reflectivity over northeast ND and northwest MN at 0124Z.

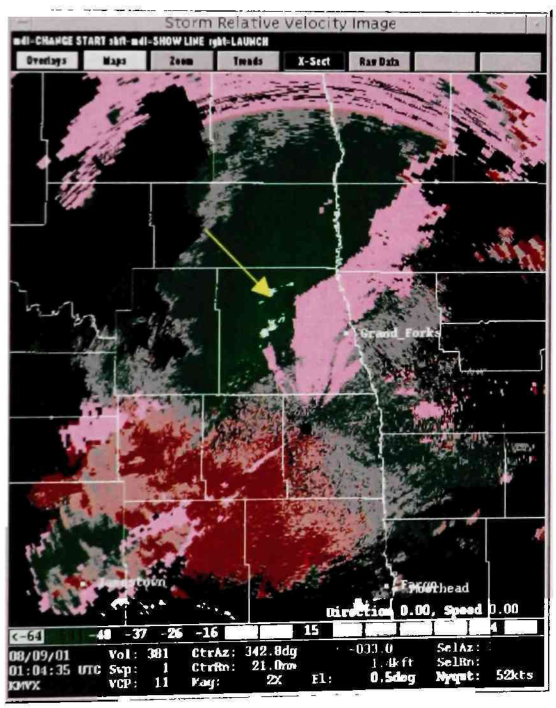

Figure 4.6. Storm relative radial velocity at 0104Z over the same general region at Figure 4.5. Yellow arrow points to the mesovortex.

levels would have shown strong rotation at the surface if the bottom few kilometers could be resolved. By 0134 Z the mesovortex is much more distinct (Figure 4.7). This vortex was visible for over an hour, shortly there after it moved far enough away from Mayville radar that the radar beam completely overshot the vortex, therefore, it is difficult to say how long the vortex lasted.

The line quickly began to bow as it moved into northwestern MN and continued as it progressed into northeastern MN where it dissipated. As in case I, severe wind reports were once again numerous across the bowing LEWP, while wind speeds were depressed in comparison to winds in eastern ND.

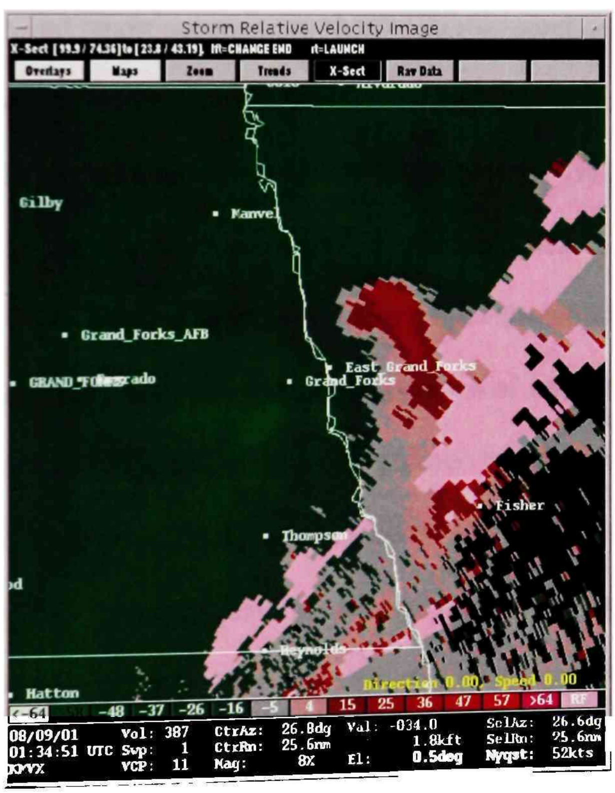

Figure 4.7. Similar to Figure 4.6, except over a small region and at 0134Z.

Case III

The first elements of convection arose at 9Z the morning of 15 June 2002. Similar to the other cases, convection slowly grew in coverage and in intensity, as by 1230Z a line of showers and thunderstorms extended from northwest NE to north central KS. By 16Z an east-west oriented LEWP formed over northwest NE, at the north end of north-south convective line stretching into north central KS. The LEWP moved southward following the main convective line. Oddly, no reports of severe wind or wind damage were indicated as the storm moved through NE, although, there were 19 reports of hail 0.75 inches or larger, one report consisting of 1.75 inch hail. Around 18Z the squall line moved into north central KS. This was accompanied by derecho initiation with the first severe wind report occurring at 1835Z. At that point, a line of strong and severe storms existed over north central KS with a number of discrete cells in central KS, while new convection formed over western portions of the state. By 21Z radar reflectivity exhibited strong convection over a large portion of KS, as two individual convective lines are evident with a number of discrete cells also noticeable. At 2108Z two tornados were reported over western KS in association of a squall line; a third tornado was reported shortly thereafter. The final tornado reported during this derecho event occurred at 2127Z in central KS and was produced by a supercell separate from the two squall lines. By 23Z one large squall line covered most of the western two-thirds of northern OK. Radar imagery also shows a number of storms over eastern CO and new storms forming in the northern Texas Panhandle. The storms over the Panhandle eventually congealed with the main squall line, extending into southeast OK. This line held together as it moved across the eastern two-thirds of TX. A large region of heavy strataform rain was noticeable as the system passed through OK and TX until reaching the Gulf Coast. Once over the Gulf of Mexico, convection quickly dissipated.

This derecho produced five wind reports over 74 kt, a relatively small number considering 153 severe winds reports. At 2139Z 15 August 2002, a 79 kt wind was reported 3 miles west of Goddard, KS. Radar showed a gust front pushing through the Goddard at this time. No other features associated with severe winds were evident. Another 4 hours and 25 minutes passed before the next recorded wind met the 74 kt threshold. Childress Municipal Airport in Childress, TX reported an 84 kt wind at 0201Z 16 August. The mechanism responsible for this severe wind report could not be determined through examination of radar data. Reflective indicated the possible presence of a rear inflow jet but was by no means conclusive. The next extreme wind event took place in Burkburnett, TX, with an 80 kt wind occurring at 0255Z. Both radar reflectively (Figure 4.8) and storm-relative velocities (Figure 4.9) show a clearly defined gust front pushing trough Burkburnett at this time. Twenty minutes later and 20 miles to the southwest, a 78 kt wind occurred in Munday, TX. The location of Munday is over 80 miles from the nearest Doppler radar. This precluded a clear determination of the cause of the severe winds. Similarly, the origin of another 78 kt wind at Archer, TX, could not be established due to remoteness from any radar. No other reports meeting or exceeding 74 kt transpired during the last 9 hours of the derecho.

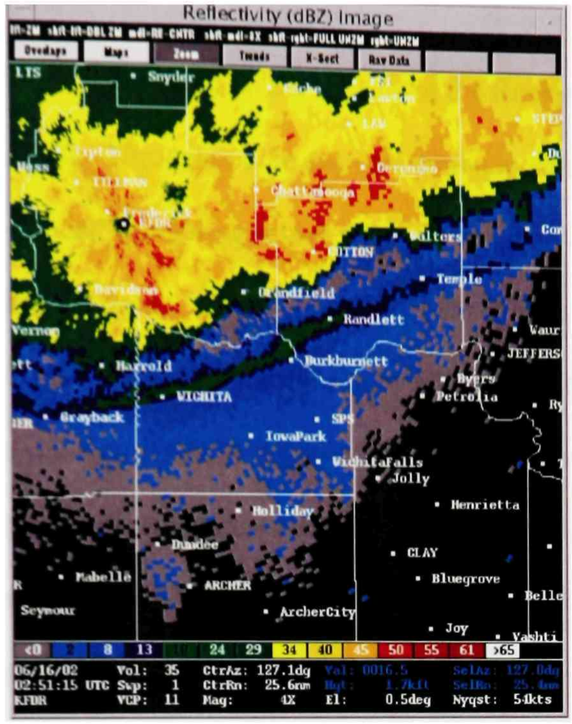

Figure 4.8. Radar reflectivity at 0151Z 16 June.

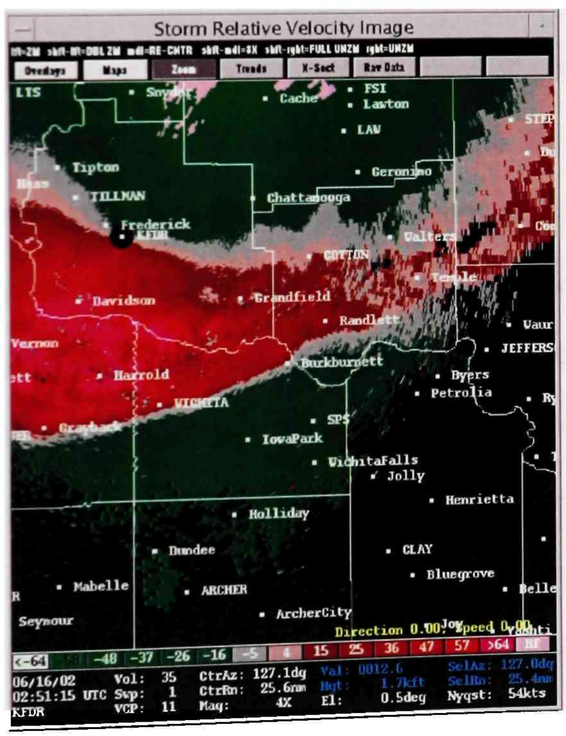

Figure 4.9. Storm-relative velocity at 0151Z 16 June

Case IV

Weak convection first appeared on the lee side of the Rocky Mountains during the morning of 25 August 2002. Throughout the day convection moved across MT as a few strong isolated storms formed generating severe wind reports. By the evening, storms moved into the Dakotas. An intense storm in northwest SD deviated from the midlevel flow turning south. This isolated storm moved across SD overnight into north central NE eventually triggering a small complex of storms to develop. By the afternoon on 26 August, the complex moved into southeast NE eventually dying by early evening, however, outflow from the complex pushed west into extreme southwest NE. This outflow was the catalyst, which caused a severe storm to develop over southwestern NE by mid-afternoon. This storm produced five tornado reports between 2105Zand 2235Z; this also signaled the onset of the derecho. At 2110Z a 76 kt wind was reported at Benkelman, NE. Radar imagery indicates the tornadic supercell over Benkelman at this time. The wind gust was likely due to a convective downdraft. An hour later the supercell produced a 79 kt wind at the Bird City, KS, airport with and a 78 kt wind 12 mile west of Goodland, KS, at 1250Z. While continuing to move south across western KS, the storm generated new convection along an eastward propagating outflow boundary, eventually forming a squall line. As the derecho moved through southwest KS, radar reflectivity depicted a type III DMCS with a strong convective cell on the southwest flank. As it moved into OK, it evolved into a type I derecho system with a strong low-level reflectivity gradient along the leading edge with a number of noticeable WEN or RIN visible. The DMCS sustained this form over the remainder of its life as it moved across central KS and eastern TX. During this time, trailing stratiform rain was present nearly 200 km behind the leading edge of the squall line. The derecho met a quick demise as it reached the Gulf of Mexico.

This derecho yielded five wind reports of 74 kt or greater. One of the reports was estimated by the public and therefore thrown out. The first three reports occurred early in the derecho's lifecycle; all were associated with a discrete super cell, not a squall line. Hence, only one event had an associated squall line coupled with a measured severe wind report. At 0305Z an 81 kt wind was recorded by ASOS at the Dodge City, KS, airport. Radar reflectivity suggests a rear inflow jet may be the origin of the strong winds. At 0238Z a WEN is visible to the northwest of Dodge City (Figure 4.10). At the same time, storm-relative velocities show an area of winds exceeding 64 kt ahead of the WEN (Figure 4.11). This is where the rear inflow jet comes in contact with the ground. As the squall line approaches Dodge City, the WEN becomes less apparent (Figure 4.12) and the intense winds decrease in aerial coverage (Figure 4.13). Shortly after passing through Dodge City, the WEN is no longer noticeable and wind magnitudes drop off substantially, with surrounding communities reporting much weaker severe winds of 50 to 60 kt.

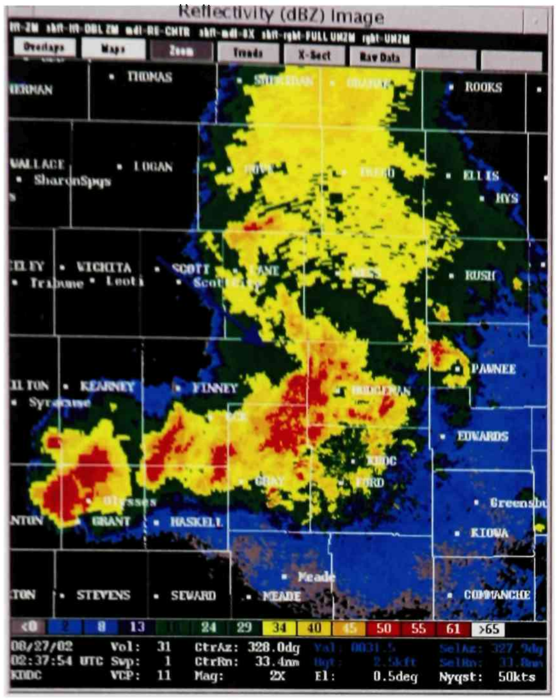

Figure 4.10. Reflectivity at 0238Z with the blue arrow pointing to the WEN.

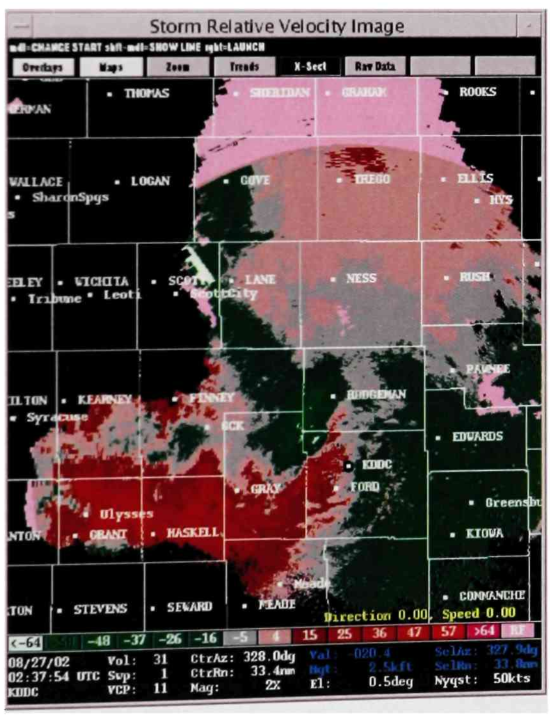

Figure 4.11. Storm-relative velocity at 0238Z. Notice the strongest radial velocities south and east of the WEN in Figure 4.12.

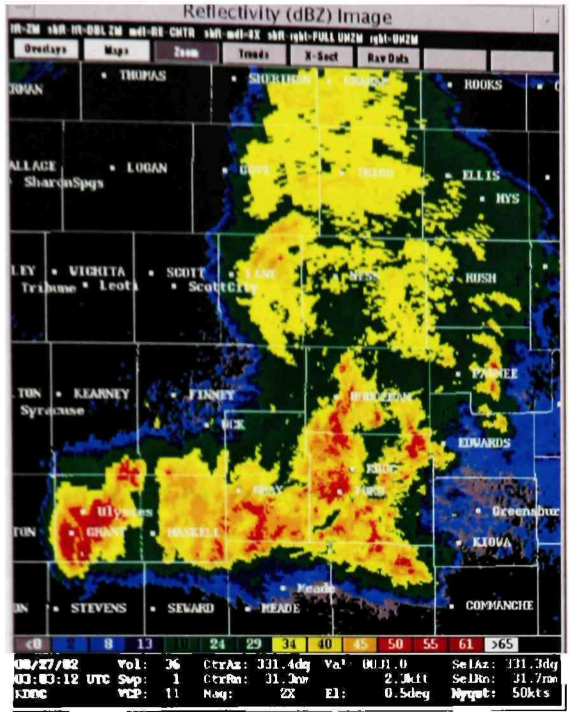

Figure 4.12. Same as Figure 4.10, except at 0303Z. A WEN is no longer obvious.

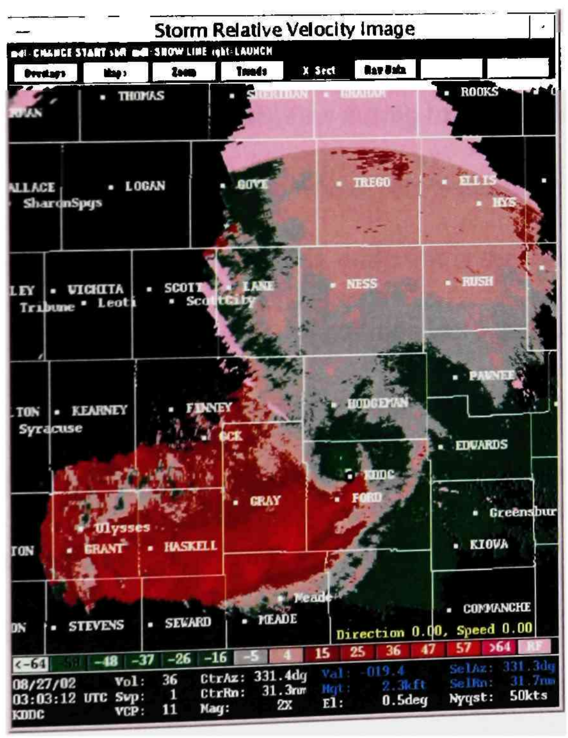

Figure 4.13. Same as Figure 4.11, except at 0303Z.

CHAPTER V

FINDINGS, COMPARISONS, AND CONCLUSIONS

Synoptic Conditions

Four warm season derechos from 2001 and 2002 were selected and studied. The synoptic-scale environments were analyzed throughout the life cycle of each derecho. This portion of the chapter will focus on similarities and differences with that of previous climatological studies, focusing on the storm environment during initiation, midpoint, and termination. Many studies using proximity soundings have been completed to determine the conditions under which derechos form and thrive. A number of previous studies have concluded these conditions are well understood. In contrast, the environments in which derechos dissipate require more examination as only a small portion of research has focused on this arena.

This study evaluated synoptic conditions during initiation, midpoint, and demise. Initiation is considered the time at which the first severe wind report occurs, while demise is where the last report is recorded. The midpoint is the point, spatially halfway between the initiation and demise locations. Wind data were gathered using the SPC storm report archive. In large part, past studies used proximity soundings to determine synoptic conditions. This study instead uses ETA analysis to determine the synoptic storm environment. A myriad of parameters have been selected for evaluation. These variables include the following, 850 and 700 mb relative humidity (rh), mixing ratio (Q), equivalent potential temperature (θ_e), 500 and 700 mb relative vorticity, surface-based CAPE, and the best lifted index. Some synoptic features are also studied to determine their effects on derechos, such as, the location of LLJ, upper-level jet (ULJ), troughs, and moisture pooling.

In all four cases it was noticed that an attendant 500 mb short-wave trough coincided with derecho development. John and Hirt (1987) also found a 500 mb short-wave trough present in every derecho case. In three cases the trough was weak with slight height falls ahead of the main wave. All of these short waves moved through the topside of a longwave ridge and eventually down the front side into northwest flow. One case showed a stronger short wave moving through the backside of a transient long-wave trough with 500 mb height falls of 60 meters over a 12-hour period. In two of the cases the short wave was evident throughout the life of the derecho, including in the region of dissipation. The remaining two derechos either outran the short wave or moved south of the main upper-level energy. Both of these derechos were sustained long after losing upper-level support. Results would suggest a 500 mb short wave is crucial in DMCS formation but is not necessary in sustaining the system. Bentley et al. (2000) findings support this as nearly 20% of derechos were not associated with a 500 mb short wave at the midpoint.

Every derecho event depicts a LLJ present at the time of initiation. During three cases, LLJ wind speeds peaked around 15 m/s; one case showed a weaker 9 m/s LLJ. In every case, the LLJ was oriented perpendicular to the upper-level flow and thus perpendicular to the derecho propagation. Over time the LLJ was found to weaken and become parallel to the derecho motion; thus decreasing storm inflow. In two of the derechos the LLJ had completely dissipated by the midpoint, while in the other two cases a semblance of the LLJ remained until shortly before dissipation. It appears the LLJ is important in the formation of a DMCS but not essential in its continuation. Initially the LLJ provides convergence to the initiation region and abundant moisture after convection forms. Once the system matures into a MCS and the cool pool becomes strong enough, convection may be sustained in large part due to forcing along the gust front. Hence, the LLJ is not a necessary forcing agent, nor is it required as a moisture supply. Of course, convection will continue only if a sufficient supply of moisture in the lower levels is provided..

The (ULJ) position was also examined. The ULJ varied in positon and strength for every case. Two cases showed a split jet with the stronger flow across Canada and a weaker branch across the southern United States. Northwest flow was evident during both split flow cases. In all cases the northern branch was situated north of derecho initiation and in three cases substantially north, thus, having no influence on convective initiation. During both split flow events, the front left quadrant of the southern jet impinged on the point of derecho formation, a situation that would contribute to large-scale ascent and therefore initiation. All derechos with an ULJ present at initiation slowly became separated from ULJ influence. By the point of derecho demise no ULJ was present within 200 km for any case. It can easily be seen the ULJ is not involved in the process of sustaining or dissipation of a derecho but maybe a precursor to derecho formation in some events, particular during northwest flow.

WAA has also been found to be required for DMCS formation and persistence. Johns and Hirt (1987) found 850 mb WAA present at the initiation point in 86% of the cases studied and in, *every* case, 850 mb WAA within 320 km. 700 mb WAA was present 74% of the time at the initiation point and within 320 km during 96% of the cases. This study found similar results as WAA typically existed near the initiation point. All four cases had 700mb WAA occurring at or very near the point of DMCS formation. However, 850 mb WAA was evident in only three of the four events studied. As mentioned in Chapter 3, CAA was taking place at initiation in Case 4. Also, no WAA could be seen within the 320 km radius, completely contradicting Johns and Hirt (1987). They examined 70 warm-season derechos and found WAA within 320 km in every case. At the midpoint, all four cases showed WAA occurring at both 700 and 850 mb. Along the path of each DMCS, WAA existed at both 700 and 850 mb; however, WAA was weaker during decay then at the midpoint and the flow was almost parallel to the DMCS. WAA is a key ingredient in derecho formation, although, anomalous events can occur. Decreased WAA advection is found to be a precursor to DMCS dissipation.

Many studies have found extremely high convectively unstable air in connection with derecho formation and evolution (Duke & Rogash, 1992, Ashley et al., 2000, Johns & Hirt, 1987, Evans & Doswell, 2001). The highest instabilities generally take place at the midpoint of the derecho track with average surfaced based CAPE values around 4500 J/Kg and a lifted index of –8 (Johns & Hirt, 1987). At the initiation point more modest instabilities are seen with CAPE values of 2200 J/kg and a lifted index at –4. Very similar results were discovered in this study. The average surfaced-based CAPE from the four cases was 2221 J/kg. At the midpoint an average CAPE of 2991 J/kg was found with 1664 J/kg at the demise point. Notice 2991 J/kg is much lower then 4500 J/kg mentioned by Johns and Hirts (1987), although this is for a much smaller number of cases and averages should be looked at with this in mind. Like other studies CAPE reached a maximum near the midpoint (Figure 5.1). However, the lifted index did not follow this trend; in fact, only one case yielded a maximum near the midpoint (Figure 5.2). Instability parameters showed an extremely large range of values, especially CAPE. CAPE values at the initiation point ranged between 0 J/kg and 4418J/kg, while the lifted index fell between -5.6 and −10.6. At derecho demise, CAPE and lifted index values range between 12 and 2650 J/kg and -.1 to −5.5, respectively. ETA analysis was erroneous at the time of dissipation for Case II and therefore not used, nor was it used in the computation of averages. For further details refer back to Chapter 3. Case III was responsible for the low CAPE and high lifted index values at the time of derecho initiation. ETA analysis from Case III showed a shallow layer cold air in connection with a backdoor cold front infiltrating the initiation region (western NE); this led to anomalous instability computations. Here elevated convection formed above the stable boundary layer. Around 800 mb an inversion layer was noticed; it is here where the convectively unstable air resided. This situation demonstrates the number of possible atmospheric conditions may lead to derecho development; forecasters need to be aware of this. It may have been beneficial to utilize the most unstable CAPE (MUCAPE) or mixed layer CAPE (MLCAPE) rather then surface-based CAPE, as they may have resolved the elevated unstable layer. MLCAPE and MUCAPE are not intrinsic to the ETA analysis and thus not assessed.

Surface and 850 mb dew points and mixing ratios clearly showed moisture pooling at or near the quasi-stationary boundary during every DMCS. At 700 mb pooling also occurs but is less noticeable. Pooling was visible at different levels in every case. For instance, Case II depicted moisture pooling at 700 and 850 mb just to the north and along the quasi-stationary boundary with no pooling at the surface. Other cases showed

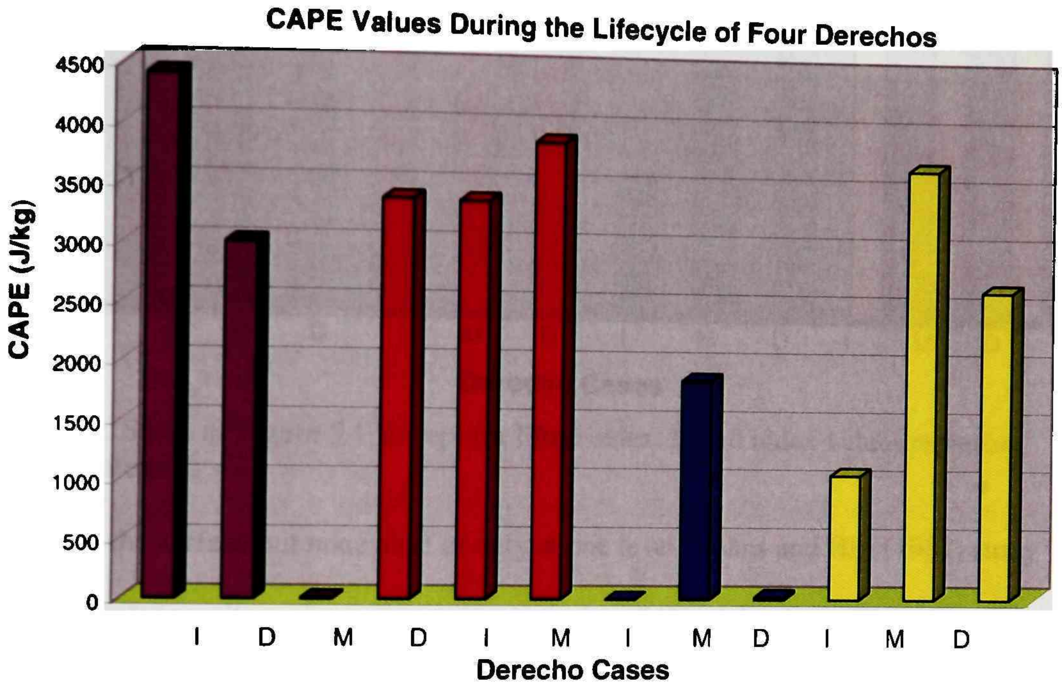

Figure 5.1. CAPE at Initiation (I), Midpoint (M), and Demise (D) during four derecho cases. Cases are in chronological order left to right.

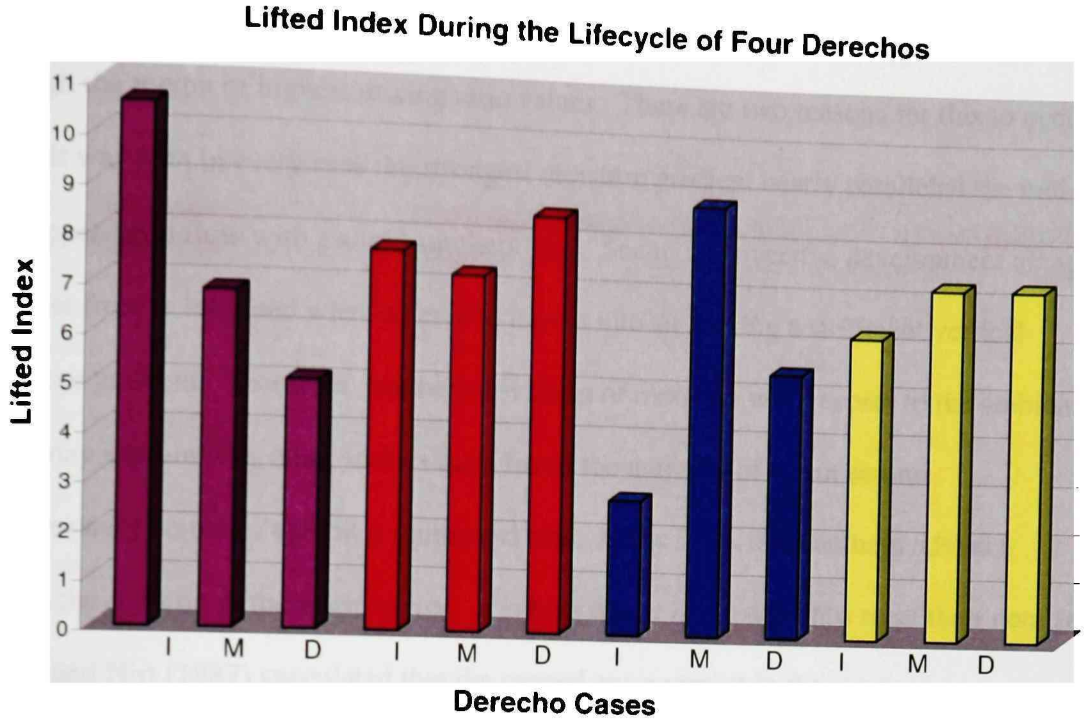

Figure 5.2 Same as Figure 5.1, except for lifted index. Lifted index values represent negative integers.

pooling at the surface but none aloft or only at one level. Johns and Hirt (1987) study yielded similar results with pooling near a boundary 74% of the time. They also noted the pooling occurred south of the boundary at the surface and near to slightly north of the boundary at 850 mb.

Moisture content was also noticed to be quite high along the entire track of each DMSC. This is apparent in the 850 and 700 mb ETA analysis mixing ratios (Table 5.1). The maximum mixing ratio value coincided with the midpoint of every DMCS at 850 mb and in three of four cases at 750 mb. As should be expected, relative humidity showed similar results with highest values at the midpoint. Table 5.1 shows striking similarities between Case I, Case II, and Case IV, as 850 mb mixing ratios virtually match at initiation, midpoint, and demise. This may indicate there may be a nexus between 850 mb mixing ratio values and DMCS formation and evolution. Every DMCS traveled through the region of highest mixing ratio values. There are two reasons for this to occur. First, it was seen in every case the strongest moisture gradient nearly paralleled the mid- and upper-level flow with a slight southern bias. Second, convective development along the gust front is inhibited when a derecho moves into air lacking a sufficient vertical moisture gradient. Therefore, southern deviation of moisture with respect to the ambient flow may explain why other studies have found the majority of warm season (progressive) derechos exhibit a southward bias. Many times this southern advance places the derecho in the warm sector. It is here where many derechos meet their demise. Johns and Hirt (1987) speculated that the capped environment in the warm sector eventually leads to the demise of many derechos. It may be true that many derechos decay in the warm sector, notwithstanding, there may be another factor. ETA analysis in this study showed higher CIN along the path of the derecho then in the warm sector during two of the derechos events. Also, the Case I derecho flourished quite some time after moving into the warm sector. Therefore, movement of a derecho into the warm sector does not guarantee derecho demise.

Moisture content in the atmosphere may be a better predictor of derecho demise. 850 mb mixing ratios were found to drop an average of 4.3 g/kg from the midpoint to demise. Case III dropped 6.8 g/kg from the midpoint to its demise while the other cases ranged between 3.1 and 4 g/kg. Of more interest is all cases saw a 3 g/kg or greater drop in mixing ratios during the 100 km. This would suggest that mixing ratios maybe a

Table 5.1. Meteorological parameters associated with derechos at initiation, midpoint, and demise. Parameters are as follows: relative humidity (RH), equivalent potential temperature (θ_e), mixing ratio in grams per kilogram (Q), Convective available potential energy in joules per kilogram, and lifted index.

Derecho Events	850 mb RH	850 mb θ_e	850 mb Q	700 mb RH	700 mb θ_e	700 mb Q	CAPE	Lifted Index
Case I								
Initiation	63.8	354	13.7	53.9	343	7.8	4418	-10.6
Midpoint	83.6	352	14.7	66.4	336	6.9	3013	-6.9
Demise	54.9	342	10.7	61.9	336	7.0	12	-5.1
Case II								
Initiation	61.0	351	13.2	49.3	338	6.5	3400	-7.8
Midpoint	83.0	352	14.5	78.5	341	8.6	3384	-7.3
Demise	62.0	342	11.1	62.3	338	7.4	3890	-8.6
Case III								
Initiation	50.6	318	5.8	18.1	314	1.5	0	-1.7
Midpoint	65.0	343	11.5	66.4	338	7.5	1873	-5.2
Demise	32.0	319	4.8	67.7	335	7.1	20	-0.1
Case IV								
Initiation	73.1	345	12.5	38.5	328	4.4	1070	-2.8
Midpoint	74.6	356	14.6	60.0	341	7.9	3696	-8.9
Demise	11.5	343	11.5	52.7	332	5.8	2656	-5.5

possible predictor of derecho demise. Similarly, equivalent potential temperature, which is highly dependent on mixing ratio, may also indicate derecho demise. 850 mb θ_e values dropped 14.5 K from the midpoint to demise region, with a noticeably large temperature drop during the last 100 km.

Analyses indicate a wide variety of synoptic conditions are possible during the formation of a derecho. Only the presence of a 500 mb short wave and an ample supply of moisture were present during each derecho event (Table 5.2). Also, moisture pooling

Table 5.2. Meterological parameters from four case studies compared to those of warm-season derechos of Johns and Hirt.

Parameter	Typical warm-season events	Four case studiy events
850 mb LLJ	Present at initiation in all cases	Present at initiation in all cases
500 mb short-wave	Present at initiation in all cases	Present at initiation in all cases
low-level moisture	Moisture pooling in low-levels	Moisture pooling in low-levels
Derecho Formation Point	North of Surface boundary	North of surface boundary
Derecho Movement	South of surface boundary	South of surface boundary
Cape	2400 J/kg at initiation 4500 J/kg at midpoint	2221 J/kg at initiation 2991 J/kg at midpoint
850 mbWAA	WAA at 850 mb within 320 km	No WAA found within 850 mb in case IV

near a surface boundary and a LLJ were present during initiation of every derecho. The presence of a 500 mb short wave, sufficient moisture, LLJ, and near by surface boundary compares well with a number of previous studies. Forecasters need to be cognizant that these components are essential for derecho formation.

High surface-based CAPEs and low lifted indices are generally good predictors to derecho development assuming wind shear profiles do not support supercells. However, as seen in case III, derechos can and do form with less than favorable stability indices. This can happen when convection is elevated, therefore, MUCAPE, MLCAPE, or elevated lapse rates may be better indicators of derecho development and should be studied in the future. High 850 mb mixing ratio and θ_e values also show promise as a precursor to derecho formation, although, once again case III indicates anomalously low values are possible. All other parameters showed limited to no correlation with derecho genesis.

Continuation and demise of each derecho depended largely if not solely on the moisture supply. All derechos paralleled the maximum 850 mb mixing ratio θ_e values. Every derecho died after moving into a region where moisture significantly decreased (Figure 6.1). Based on this study, 850 mb mixing ratios and θ_e show significant promise in forecasting derecho track and demise. Only a limited number of cases were evaluated, hence, an examination of a much larger dataset is needed for conclusive results.

Radar Analysis

Analyses of WSR-88D radar data were performed along the path of each derecho. In attempt to determine the source of the extreme wind, an emphasis was placed on analyzing reflectivity and radial velocity data near the time of extreme wind reports. It was found that a large variety of radar reflectivity patterns exist as derechos continuously evolve during the lifecycle and should not be placed into four derecho categories, as Przybylinski and DeCaire (1985) suggest. At some points a clear, continuous squall line was present. In other instances the squall line was broken and composed with a number distinct cells within the line or composed of many smaller

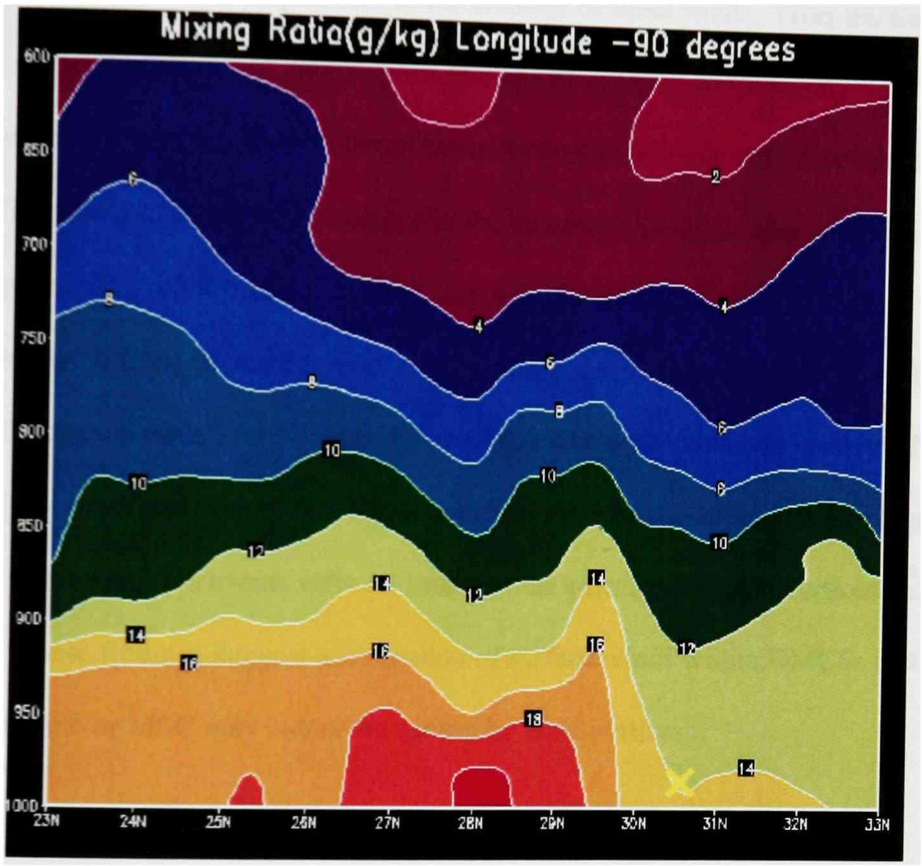

Figure 5.3. Vertical cross-section of mixing ratios from case IV. Represents a typical moisture field during a derecho event. The yellow x denotes the point of derecho demise. Notice the large decrease in moisture in the vicinity of derecho demise.

bowing segments within the line. Sometimes the squall line showed a distinct bowing pattern; while at other times no bowing took place. In some instances no squall line existed, only a cluster of storms were present

Closer inspection of radar imagery, during extreme wind events, suggests different mechanisms are responsible in the creation of these winds. Over the total lifetime of the four derechos, SPC reports showed 11 extreme wind events. Two of the non-determined cases were a product of the radar beam scanning well above ground level. This was due to the large distance of the nearest WSR-88D radar with respect to wind reports The other non-determined case was due to inconclusive evidence. Two of the reports were from estimated winds and therefore removed from the data set. Discrete super cells caused three of the events and therefore not examined more closely. The passage of a gust front caused one report, another was in association with a rear inflow jet. The remaining two events were all linked to the existence of mesovortices near the surface. These findings suggest acceleration of surface winds within DMCSs and in fact any squall line or MSC may indeed be caused by mesovortices.

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