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Discrimination of the Formation and Intensity of Progressive Derechos Based on the Environmental Conditions of Simulated Events

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By

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The purpose of this research is to simulate warm-season mesoscale convective systems (MCSs) using the Weather Research and Forecasting Model (WRF) to determine whether modeled atmospheric variables are capable of discriminating between derecho formation and intensity. Fifty total events are selected with half being derecho-producing MCSs and half being non-derecho producing MCSs. WRF is used to model each event with a high-resolution domain centered over the Midwest using the North American Regional Reanalysis (NARR) dataset as initial and boundary conditions. Atmospheric conditions downstream of the MCS damage path are compared to thresholds established by previous research to determine if the model accurately simulates the expected environment. The goal of the research is to gain insight into how well a high-resolution model can simulate the environment that is expected. It is anticipated that the model will be able to distinguish between environments associated with a derecho-producing MCS and a non-derecho MCS.

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CHAPTER I

INTRODUCTION

The focus of this study is on derechos, which are convectively induced, long-lived straight line wind events. A derecho was first defined as a concentrated area of wind reports of greater than 50 knots with a major axis of 400 km, a nonrandom pattern of occurrence (singular swath for progressive derechos), at least three reports separated by at least 64 km of either 65 knots (kt) or greater wind or F1 (EF1) magnitude tornado damage, and no more than three hours of time elapsed between successive wind damage reports (Johns and Hirt 1987). For this study, the Johns and Hirt (1987) definition of a derecho is very close to what will be considered a “moderate” derecho event. The exact definition of a derecho can have important implications during research, demonstrated in one study of the climatology of derechos that resulted in a much larger number of derecho cases when the requirement for well-separated significant wind damage (65 kts or greater) was not included (Coniglio and Stensrud 2004). As a result of these variations, different definitions of a derecho will be used for this study in order to separate derecho cases based on intensity (low-end, moderate, and high-end).

Derechos have been extensively studied over the past decades because of their major destructive impacts on human life and property (Storm Prediction Center 2004). A study by Ashley and Mote (2005) of derecho hazards in the United States found that in an 18-year period there were 153 fatalities (average of 8.5 per year) and over 2,600 injuries attributed to this meteorological phenomenon. During the period from 1986 to 2003 derecho fatalities exceeded those of 88% of tornadoes, with a single derecho event responsible for up to eight fatalities and 204 injuries (Ashley and Mote 2005). In terms of the economic impact, insured losses resulting from derechos often exceed $100 million, which is equivalent to many recent U.S. hurricanes and to some of the most damaging tornadoes in U.S. history (Ashley and Mote 2005). The impact of derechos on human life and property presents a clear need for better forecasting of this often overlooked, major hazard (relative to tornadoes, hurricanes, etc.).

Derecho Types

There are two types of derecho events - progressive and serial (Storm Prediction Center 2004). Serial derechos are usually accompanied by a line echo wave pattern (LEWP) with multiple bow echoes developing, and are usually associated with strong kinematic forcing and an accompanying cyclone (Johns and Hirt 1987). The primary focus of this research is on the progressive type of derecho, which is characterized by a short, bowed-out squall line with a bulge in the direction of the mean wind (Johns and Hirt 1987). This type of derecho accounts for approximately 75% of all derechos, depending on exact classification (Johns and Hirt, 1987; Ashley and Mote, 2005). Additionally, this type of derecho is weakly forced by dynamics, typically occurs in the warm season, and has the largest amounts of convective available potential energy (CAPE) of all of the types of derechos while also exhibiting strong storm-relative inflow at the lower levels due to rapid convective system movement (Doswell and Evans 2003). Other important factors in derecho maintenance for weakly forced systems is redistribution of precipitation to the rear of the leading line of convection and a tendency to form in quick succession of one another (Doswell and Evans 2003). One study found that 62% of derechos in a ten year period of study were part of a derecho series - having occurred in a similar synoptic environment and within 72 hours of each other (Ashley et al. 2005). This further complicates relief efforts as these derecho series will often occur over the same regions.

Progressive derechos have a distinct spatial and temporal distribution within the contiguous United States. Multiple climatological studies of progressive derechos in the United States indicate maxima in the Southern Great Plains and the Upper Midwest into the Ohio Valley (Coniglio and Stensrud, 2004; Ashley and Mote, 2005); however, progressive derechos can be found almost anywhere east of the Rocky Mountains. Temporal distribution for progressive derechos can be separated into seasons and time of day. As mentioned earlier, with progressive derechos being warm season events, the vast majority occur during the summer months (May, June and July). Similarly, multiple studies have found that progressive derecho initiation is closely associated with the diurnal heat cycle (Johns and Hirt, 1987; Bentley and Mote, 1998), with the majority of derechos in one study initiating between 0400 and 1600 UTC (Bentley and Mote, 1998). However, this same study (Bentley and Mote 1998) found a relatively large number of derechos (26%) initiating between 1000 and 1600 UTC, sometime displaced from the diurnal cycle and contrary to previous studies (Johns and Hirt 1987). This is likely due to the Bentley and Mote (1998) study including cool season events, which the Johns and Hirt (1987) study did not do.

Atmospheric Variables Related to Derecho Formation and Evolution

There are certain thermodynamic components and other dynamic components that could possibly determine why a progressive derecho occurs. Previous studies have defined the differences in what variables contribute to an MCS producing a derecho. A study by Evans and Doswell (2001) showed that kinematics alone can discriminate between derecho producing systems and non-severe MCSs, but that thermodynamic components must also be in place; however, there is research that suggests that thermodynamic variables alone are good at discriminating between derecho producing systems and non-severe MCSs. Cohen et al. (2007) found that mid-level lapse rates are better than equivalent potential temperature and CAPE at discriminating between derecho-producing, severe, and weak MCSs, while Kuchera and Parker (2006) found that CAPE (including mean layer CAPE, most unstable CAPE, and downdraft CAPE), humidity aloft, and lapse rates aloft were decent at discriminating between damaging and non-damaging winds, while steep surface lapse rates were not. Additionally, Coniglio et al. (2007) found that lapse rates over the convective cloud layer and CAPE are good at discriminating between mature and weakening MCSs. Despite the potential for thermodynamic variables to discriminate between derecho-producing MCSs and non-derecho producing MCSs, kinematic variables are consistently found to perform better than thermodynamic variables. As stated by Kuchera and Parker (2006), "Large ambient ground relative wind speeds in the lower troposphere … should be the highest consideration when forecasting long-lived damaging convective windstorms." The influence of ambient wind should not be understated, as Kuchera and Parker (2006) go on to explain that these winds lead to fast-moving convective systems that result in the shear necessary to maintain the gust front. Therefore, thermodynamic variables (such as CAPE) are important requirements for cold-pool driven, warm season MCSs, but kinematics should be examined more closely for discrimination potential.

Kinematics alone have been shown to be able to discriminate between derecho producing systems and non-severe MCSs once it has been established that sufficient thermodynamics are in place. In similar thermodynamic environments, strength of the mean flow (and its effects on movement speed) enhances the potential for severe wind (Evans and Doswell 2001). Cohen et al. (2007) suggest that mean low to upper-level wind speeds and deep wind shear are the best discriminators between weak, severe, and derecho-producing MCSs, while Kuchera and Parker (2006) found that ground relative wind velocity was most effective at discriminating between damaging and non-damaging winds. An additional study found that the deep shear vector is the best discriminator between mature and weakening MCSs, while deep mean wind is also a good discriminator (Coniglio et al. 2007). While all of these kinematic variables could be examined, the focus will be on the Evans and Doswell (2001) study that led to the creation of the derecho composite parameter (DCP) during the NOAA Hazardous Weather Testbed 2005 Summer Experiment (Coniglio et al. 2005). Therefore, for the purposes of this study, the focus of kinematic derecho discrimination will be on the magnitude of the wind shear vector from 0-6 km above ground level (AGL) and the magnitude of the mean wind vector from 0-6 km AGL. These are the two kinematic variables used in the DCP calculation, along with thermodynamic variables of most unstable CAPE and downdraft CAPE. For the purposes of this study, surface CAPE will be the only thermodynamic variable used, as this is straightforward way to ensure instability is present. The kinematic variables will be the focus for discrimination between the formation and intensity of the derechos.

Numerical Simulations of Convective Windstorms

There has been extensive research on modeling of severe straight-line winds within MCSs. One study by Done et al. (2004) found that a high-resolution, 4-km grid spacing in WRF that explicitly treated convection (did not use a cumulus parameterization) was able to predict identifiable MCSs with accurate position in time and space to the observed system, while 10-km spacing and parameterized convection were not able to do so. As a result, the modeling approach for this project will include a convection-allowing 4-km spatial resolution to more accurately depict the physical environment of the convective windstorms. Although this study is primarily concerned with environmental factors that lead to derecho formation, it is important to maintain the integrity of the environment by accurately modeling the MCS itself.

There have been numerous studies that attempt to accurately simulate a derecho within a high-resolution weather model. A study by Coniglio and Stensrud (2001) simulated a rapidly moving curved squall line with embedded bow echoes and severe near-surface winds for over eight hours using the MM5 model. Weisman et al. (2013) extensively studied the May 8th, 2009 Superderecho with a high-resolution WRF model run. A more recent study simulated a derecho that occurred in Estonia in 2010, providing a quantitative background that could be used for further analysis (Toll et al. 2014). These studies simulate a single derecho with a mesoscale model finely tuned to produce the near-surface winds that occurred during the event. The goal of this study is to use a configured version of the WRF that is similar to a high-resolution operational mesoscale model. Rather than focusing on raw output of near surface wind gusts, the environment downstream of the MCS is examined to determine whether or not a derecho is likely to occur based on pre-defined thresholds of specific kinematic and thermodynamic variables. This type of study differs considerably with other recent studies that only simulate a single derecho event in that the accuracy of the actual simulated derecho is not the focus; rather the focus is on the simulated atmospheric environment associated with the intensity of the derecho.

Project Objectives

The project objectives are to compare selected environmental meteorological variables (CAPE, 0-6 km AGL wind shear and 0-6 km AGL mean wind) with thresholds established by previous research to determine if the WRF simulation framework can predict the environment associated with a derecho-producing MCS or non-derecho producing MCS. This will be done by simulating 50 MCS (25 derecho producing, 25 non-derecho producing) events in the Midwestern U.S. during the warm season (May-August) from the years 1995 to 2001. This will be done to determine the accuracy of WRF in predicting derecho production solely based on environmental thermodynamic and kinematic variables instead of assessing the accuracy of the simulation of the actual derecho. These results can be used to assess the utility of an operational convection-allowing model to define derecho formation potential, and can also be used to generate new thresholds to further discriminate between derecho intensity (low-end, moderate and high-end).

CHAPTER II

METHODS

The Weather Research and Forecasting (WRF) model is used to simulate 25 derecho-producing MCSs and 25 non-derecho-producing MCSs that occurred in the Midwestern U.S during the warm season (May, June, July and August). All MCSs will be simulated using WRF to examine their thermodynamic and kinematic components in relation to pre-defined discriminatory thresholds to determine if WRF is able to produce the environment conducive to derecho formation even if a simulated derecho does not form. If this is the case, WRF output is further examined to see if any variables are able to also discriminate between different intensities of derechos (low-end, moderate and high-end).

The events for the WRF simulation were selected from a seven year period beginning in 1995 and ending in 2001. As previously stated, there will be 50 total events with 25 of those events being derechos and the other 25 being non-derecho producing MCSs. The derecho cases are further split up into low-end, moderate and high-end severity. These categories have been defined by Coniglio (2015), and as mentioned earlier the "moderate" derecho events are closest to the original Johns and Hirt (1987) definition. However, derechos of all intensities in this study will meet the following criteria (which is similar to Bentley and Mote (1998)):

1. There must be a concentrated area of wind reports consisting of convectively induced wind damage and/or wind gusts of 26 ms^{-1} (50 kt) that are produced by convection associated with an organized MCS. This area must have a major axis length of at least 400 km.

2. The reports within this area must also exhibit a nonrandom pattern of occurrence. That is, the reports must show a pattern of chronological progression, either as a singular swath (*progressive*) or as a series of swaths (*serial*).

3. No more than 2.5 h can elapse between successive wind damage (gust) events and each report must be within 200 km of any other report in the wind-gust swath.

4. The associated MCS, as indicated by surface pressure and wind fields, must have temporal and spatial continuity; however, movement of radar echoes associated with the system need not be continuous.

5. Multiple swaths of wind damage (including gusts) must be a part of the same MCS as indicated by the available radar data.

The above criteria are required for a "low-end" derecho classification. For a "moderate" derecho classification, there must also be at least three reports, separated by 64 km or more, of either F1-type damage and/or convective gusts of 33 ms^{-1} (64 kt) or greater during the MCS stage of the event. To be considered a "high-end" derecho classification, all of the above criteria must be met plus there must be at least three reports of convective gusts of 38 ms^{-1} (75 kt), or comparable damage reports, separated by at least 64 km, at least two of which must occur during the MCS stage of the event. This study uses a list provided by Coniglio (2015) in which each derecho event is classified in this manner. Derecho events were randomly chosen from the list of defined events that occurred in the Midwestern U.S. during the months of May, June, July and August. There were a total of eight low-end events, nine moderate events, and eight high-end events selected for analysis. For specifics on the events see Appendix A. Non-derecho producing MCSs are taken from the same time period (1995-2001) using the same spatial and temporal criteria. Using the same time period is useful because it is easier to find MCS cases that are non-derecho producing, since the list of derechos provided by Coniglio (2015) is comprehensive of all derechos during this period (1995-2001). Additionally, this allows the derecho cases to be compared to non-derecho cases that occurred during the same time period. These cases were chosen manually using the SPC National Severe Weather Database Browser and archived NEXRAD Base Reflectivity data from the Iowa Environmental Mesonet website (IEM 2016). These cases were also run in the same WRF simulation domain with identical model settings.

Data used for initialization of the WRF model simulations was taken from the NCEP North American Regional Reanalysis (NARR) dataset, which has a spatial resolution of 32-km; however, the WRF simulation domain will have a spatial resolution of 4-km, which is necessary to provide a convective allowing resolution that more accurately simulates all convective processes that would not be possible on a more coarse resolution. Version 3.6.1 of the WRF model was used with a domain centered at 40° N and -92.5° W with a grid size of 550 by 400 (Figure 2.1). The model used 45 vertical levels concentrated at the surface in a hyperbolic tangent profile with a model top of 100 mb. The WRF setup is based on the convection-permitting simulations used for the NCAR spring real-time convection forecast over the U.S. in 2013 (NCAR 2016). The associated parameterization schemes for this setup are as follows: microphysics, the New Thompson et al. (2005) scheme; longwave and shortwave radiation, the RRTMG (rapid radiative transfer model for general circulation model) scheme; the Noah land surface model; planetary boundary layer, the Mellor-Yamada-Janjic scheme. Since the model is being run at a convective-allowing resolution, no cumulus parameterization was used.

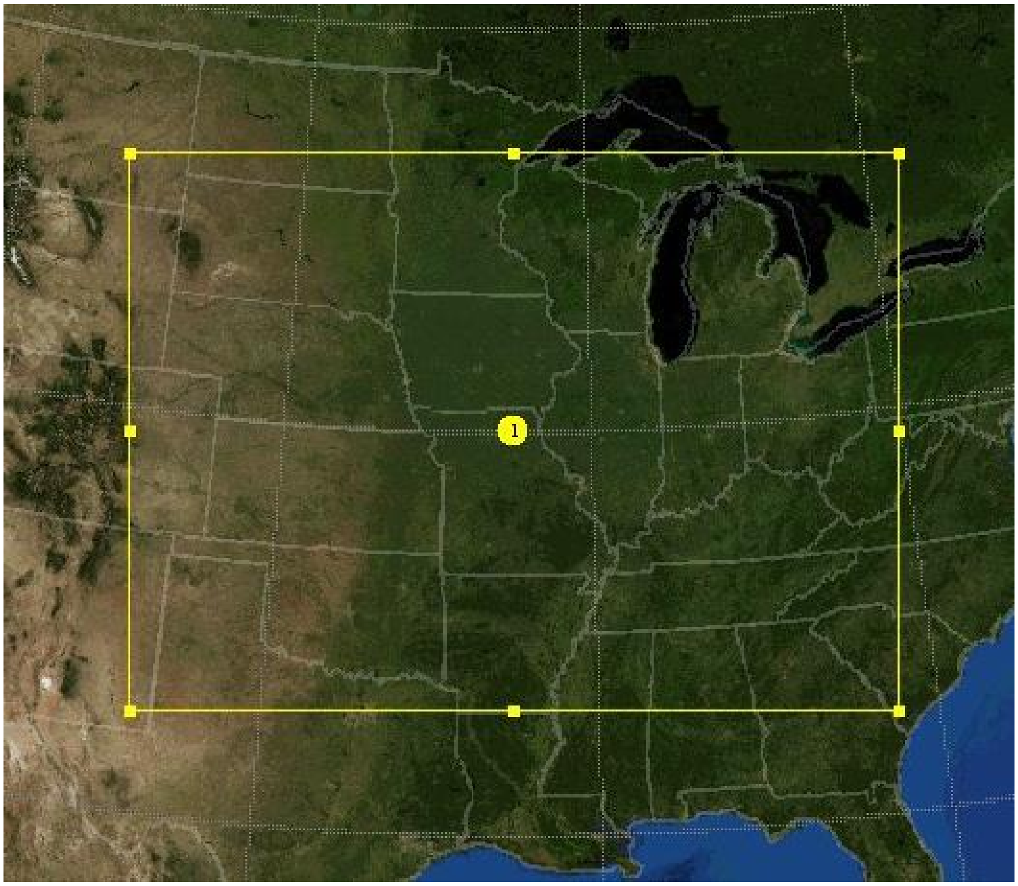

Figure 2.1 Domain centered over the Midwestern U.S. for specialized 4-km WRF

Environmental values were spatially and temporally chosen in a similar fashion to the original research by Evans and Doswell (2001) in which the proximity soundings were selected that were uncontaminated by convection and located within or near the ensuing damage path. These “proximity soundings” in the Evans and Doswell (2001) study are observational, originating from radiosonde stations managed by the National Weather Service (NWS) Upper-air Observations Program (NOAA 2016). In order to be used in the Evans and Doswell (2001) study, the observed sounding must also have been taken within both two hours and 167 km (100 mi) of the wind damage path or bow echo location on radar charts. In addition to strict spatial requirements for proximity soundings, there is also the temporal restriction of either a 0000 UTC or 1200 UTC sounding (usually 0000 UTC due to the diurnal cycle), as these are the times of day that radiosondes are routinely launched. Using these criteria, the ideal proximity sounding locations downstream of the MCS are identified on a case-by-case basis using existing radiosonde locations, the values of the variables from the WRF model output are then recorded and used for analysis.

Figures 2.2 and 2.3 show examples of model output for 0000 UTC 10 May 2000 with surface CAPE (Figure 2.2) and deep mean wind magnitude (Figure 2.3) displayed with selected proximity sounding locations. The first damaging wind report for this case occurred at 1937 UTC 9 May 2000, at 38.63 N latitude and -88.95 W longitude. The last wind report occurred at 0134 UTC 10 May 2000, at 42.7 N latitude and -81.55 W longitude. Since the output is valid at 0000 UTC 10 May 2000, the leading edge of the MCS is approximately located between the first and last wind reports, with surface CAPE giving a general idea of the leading edge of the bow echo where there is a tight surface CAPE gradient in Illinois and Ohio. The single chosen proximity sounding for this event is the only sounding location directly ahead of the MCS in Wilmington, Ohio. This corresponds to a surface CAPE value of 1840 J kg^{-1} and a 0-6 km AGL mean wind value of 15.0 m s^{-1}. The 0-6 km AGL wind shear value is also recorded (15.6 m s^{-1}).

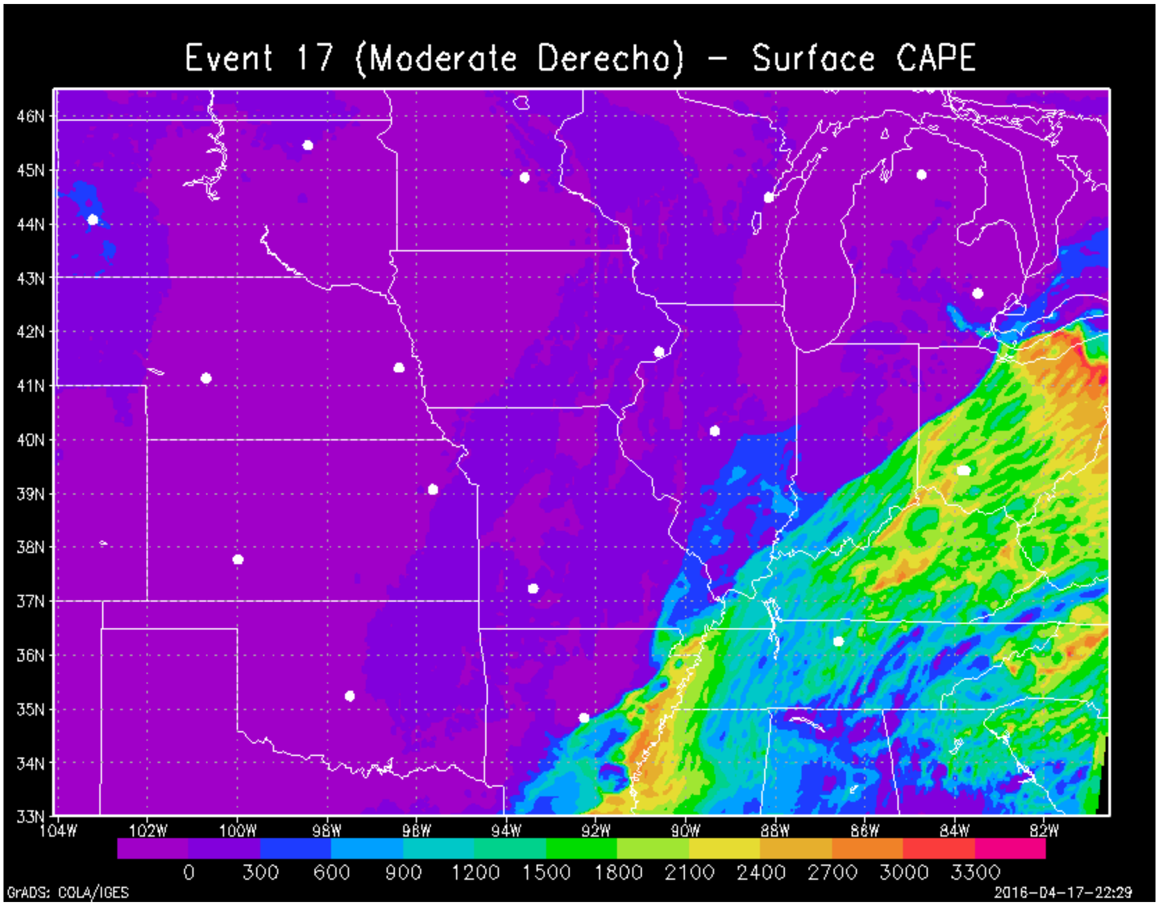

Figure 2.2 Example graphical output of Surface CAPE (J kg^{-1})

Valid at 0000 UTC 10 May, 2000 for Event 17 (moderate derecho). Small white circles represent proximity sounding locations.

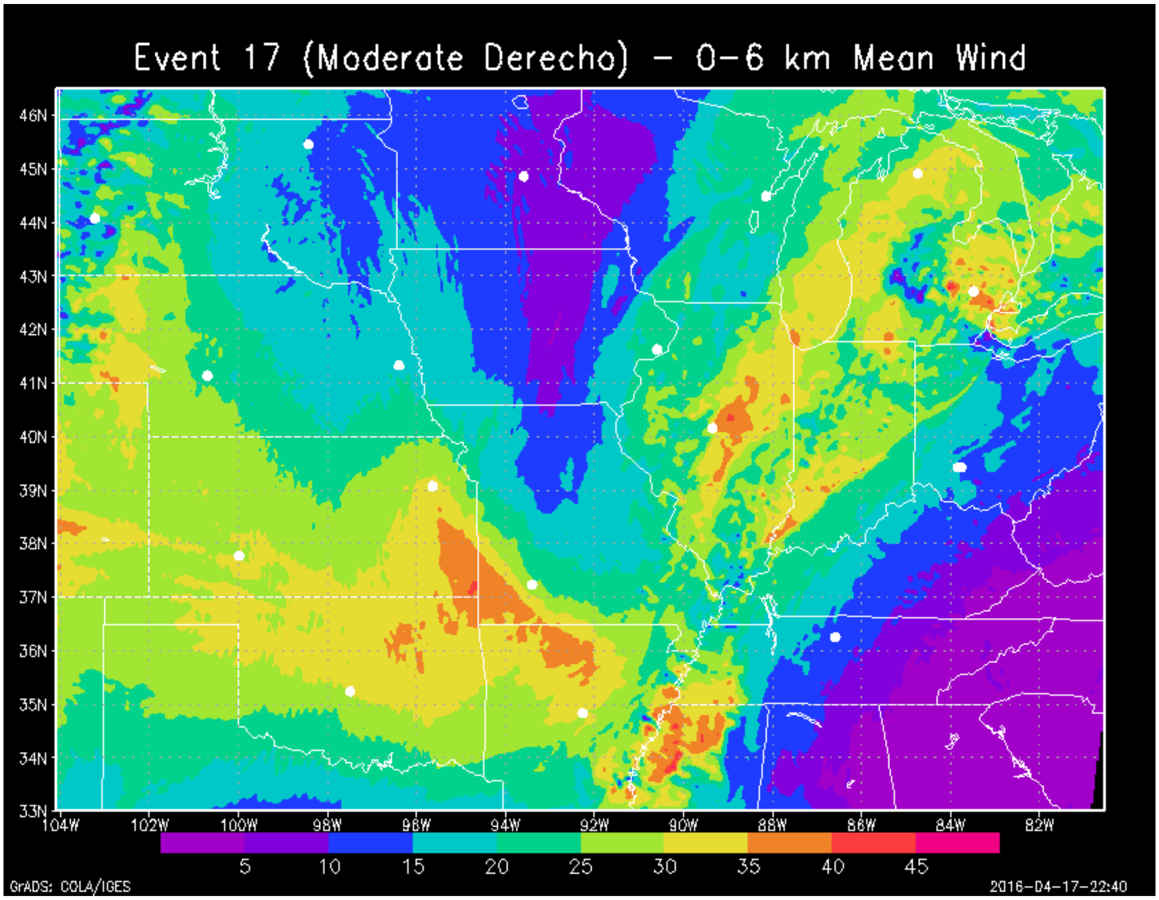

Figure 2.3 Example graphical output of 0-6 km AGL mean wind (m s^{-1})

Valid at 0000 UTC 10 May, 2000 for Event 17 (moderate derecho). Small white circles represent proximity sounding locations.

With all of the above proximity sounding criteria in mind, the methods of the Evans and Doswell study (2001) are used as the fundamental basis for this study. However, this study is not truly duplicating the exact methods of the Evans and Doswell (2001), as proximity soundings in this study are really "modeled" point soundings, rather than proximity "in-situ" soundings. This is an important distinction that gives this study relevance, as environmental conditions for derecho formation need to be verified within the model before the modeled environmental data can be used for derecho formation and intensity prediction. Therefore it is important to note that although points can theoretically be chosen from anywhere on the 4-km modeled grid, this study instead replicates the spatial and temporal criteria of Evans and Doswell (2001) by taking snapshots of the model simulations at fixed points in space (NWS upper-air locations) and time (0000 UTC and 1200 UTC) in the environment downstream of the MCS. This will allow the observational study to be verified within a high-resolution model framework. In order to increase the number of usable modeled proximity soundings the times were adjusted up to 3 hours prior to 0000 UTC and 1200 UTC if the leading edge of the MCS had recently traversed over a radiosonde location and contaminated the sounding. This adjustment is easily made since there is hourly output for the high-resolution WRF data, and was ultimately only applied to nine of the 69 total cases. There is much insight to be gained on the operational forecasting and prediction of derecho formation by verifying the observational study of Evans and Doswell (2001) within the context of high-resolution numerical weather prediction.

This study primarily examines the kinematic variables (0-6 km AGL wind shear and 0-6 km AGL mean wind) which are expected to have the highest degree of discrimination (Evans and Doswell 2001). These values are compared to previous statistical thresholds established by Evans and Doswell (2001) with their proximity sounding research. Figure 2.4 shows the relevant box and whisker plots for wind shear, while Figure 2.5 shows the relevant box and whisker plots for mean wind and system speed based on results from Evans and Doswell (2001). Deep mean wind (Figure 2.4) is shown to be the better discriminating kinematic variable in Evans and Doswell (2001) with separation between the two interquartile ranges (IQR) of the non-derecho and derecho cases respectively. Deep layer wind shear (Figure 2.5) is not quite as discriminatory with overlap occurring between the respective interquartile ranges (Evans and Doswell 2001). If the modeled environmental variables are capable of discriminating between derecho-producing MCSs and non-derecho producing MCSs based on the pre-defined Evans and Doswell (2001) criteria, then new thresholds may be determined to further establish intensity of the derecho-producing MCSs (low-end, moderate, and high-end variable designations).

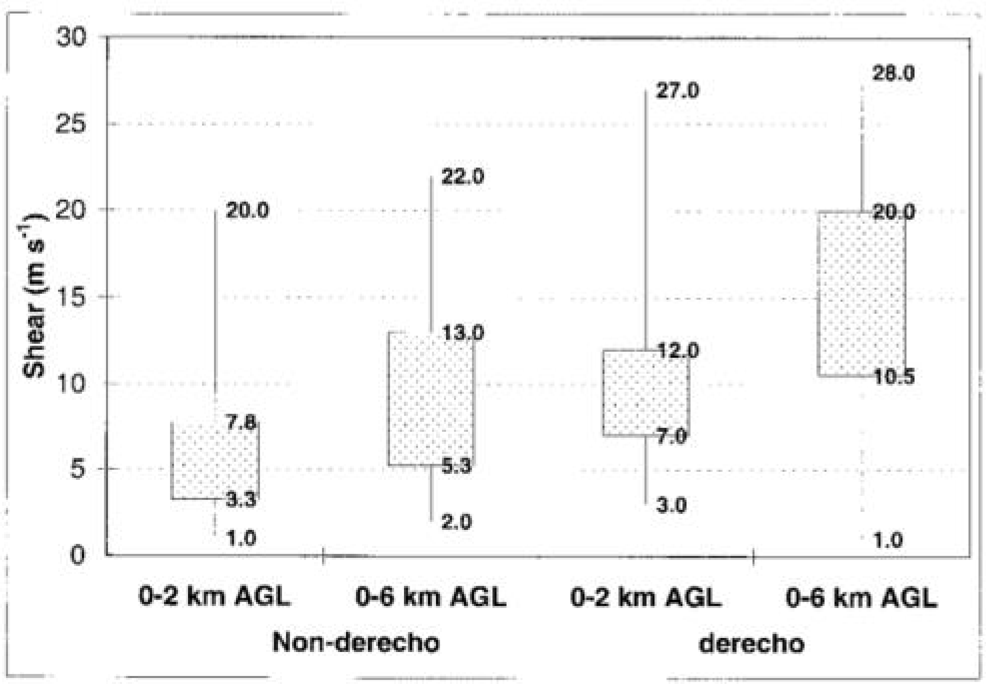

Figure 2.4 Observed Wind Shear Box Plots from Evans and Doswell, 2001

0-2 km and 0-6 km AGL wind shear vectors for both non-derecho and derecho producing weakly forced events from observational study that established derecho composite parameter (from Evans and Doswell 2001).

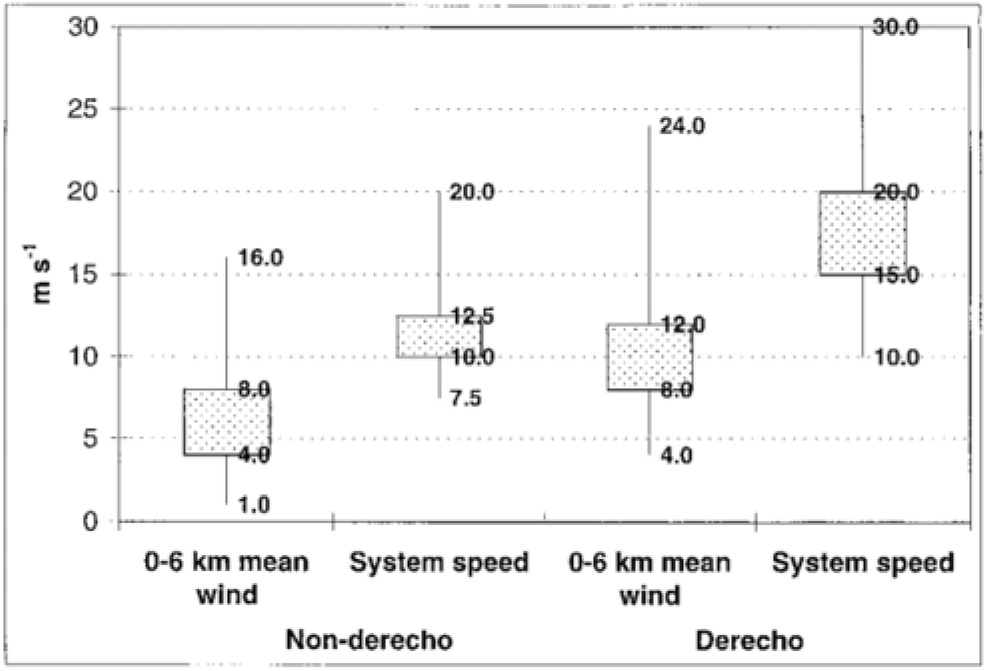

Figure 2.5 Observed Mean Wind and System Speed Box Plots from Evans and Doswell, 2001

0-6 km mean wind vectors and system speed for both non-derecho and derecho producing weakly forced events from observational study that established derecho composite parameter (from Evans and Doswell 2001).

The discriminatory values previously discussed are derived from the Evans and Doswell (2001) study and are described in more detail with the creation of the derecho composite parameter (DCP) during the NOAA Hazardous Weather Testbed 2005 Summer Experiment (Coniglio et al. 2005). The thermodynamic values in the DCP are equivalent to the 25th percentile value of the non-derecho dataset (considered common) while the dynamic variables are equivalent to the 75th percentile value (considered uncommon). As discussed earlier, the thermodynamic variables are part of the equation only to remove the assumption that favorable thermodynamics already exist (Coniglio et al. 2005). Since this study is only considering weakly forced, warm season derechos, it is reasonable to assume that favorable thermodynamics exist in each case. Even still, surface CAPE is recorded and analyzed to confirm the thermodynamic environments before proceeding to the anticipated discriminatory kinematic environments. The kinematic values correspond to 10.3 m s^{-1} (20 kt) for deep layer wind shear, and 8.2 m s^{-1} (16 kt) for deep layer mean. These are the discriminatory values used to form contingency tables, the basis for determining the predictive skill of a particular threshold. For example, if the deep layer mean wind for a particular proximity sounding is 8.0 m s^{-1}, then it is predicted that case is a non-derecho producing MCS case. In addition to contingency tables, thermodynamic and kinematic variables were separated by MCS formation type (derecho or non-derecho) and their associated variables visualized in box and whisker plots. Furthermore, both datasets (derecho and non-derecho producing MCSs) were bootstrapped (n=1000) in order to increase the number of data points being used for the study and modify/normalize the resulting statistical distribution. These bootstrapped data are then used to create confidence intervals (95%) which are useful for determining the statistical difference in kinematic variables. In addition to analyzing confidence intervals, permutation tests (α=0.05) were also computed to provide additional insight on the similarities/differences in the datasets. And finally, in order to further examine the predictability of derecho formation, Brier score and skill scores were computed.

CHAPTER III

RESULTS AND DISCUSSION

Discriminatory Analysis

There were 69 total modeled proximity soundings that were derived from 44 of the 50 total cases. Six of the 50 cases did not have any modeled proximity soundings due to insufficient criteria. All six of these cases were non-derecho cases (numbers 27-29 and 41-43). These modeled point soundings were first separated based on derecho cases (46 of the 69) and non-derecho cases (23 of the 69). These numbers are fairly representative of the NOAA Hazardous Weather Testbed 2005 Summer Experiment that created the DCP, with 51 derecho and 31 non-derecho proximity soundings being used (Coniglio et al. 2005). This separation of cases allows us to examine the environmental variables (Surface CAPE, deep wind shear, and deep mean wind) in order to determine the models ability to discriminate between the two. The point soundings from the derecho cases were further divided into low-end (12 of the 46), moderate (24 of the 46), and high-end proximity soundings (10 of the 46). Ideally there will be further discrimination within the model to discriminate between relative severities of derechos based on the environmental variables.

Thermodynamic characteristics of the environment are first analyzed before proceeding to the discriminatory kinematic variables. Box and whisker plots are made separating derecho cases and non-derecho cases (Figure 3.1). Surface CAPE is commonly above 2000 J kg^{-1} in both derecho and non-derecho cases. This is expected since non-derecho producing MCSs form in very similar environments to their progressive derecho producing counterparts. The mean for derecho cases is 3252 J kg^{-1} while the mean for non-derecho is 2951 J kg^{-1}. There are 13 (of the total 69) modeled proximity soundings that had less than 2000 J kg^{-1} of CAPE and only one modeled proximity sounding had less than 1000 J kg^{-1} of CAPE.

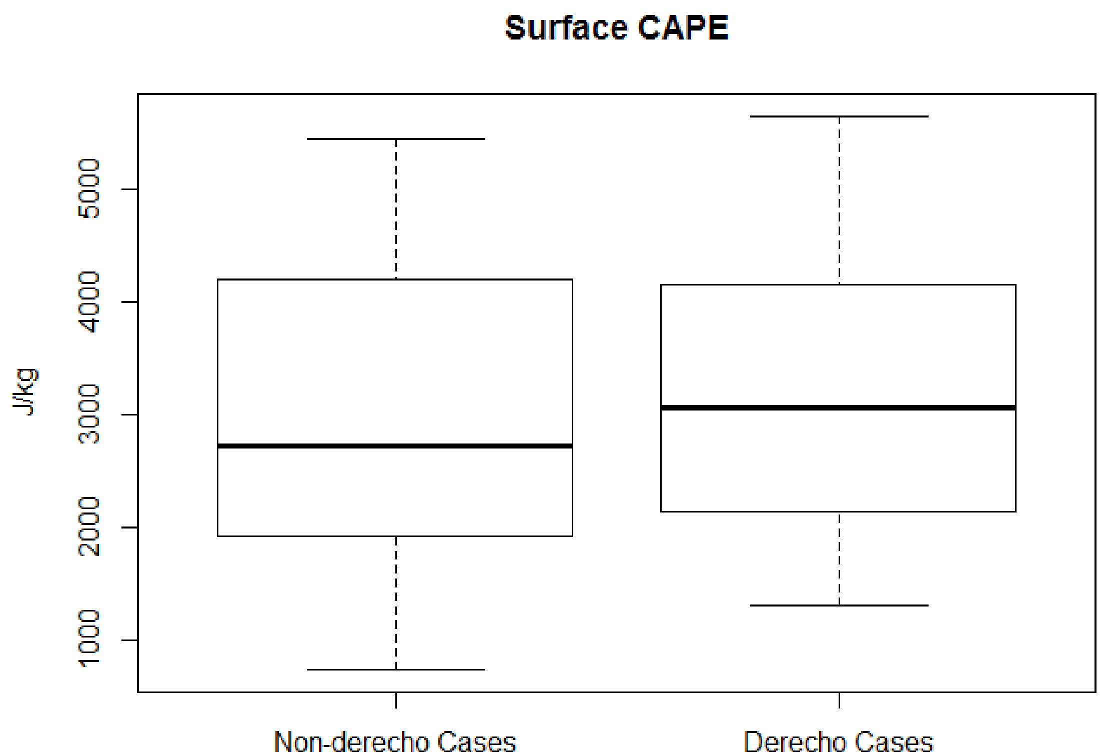

Figure 3.1 Surface CAPE Box Plot

Plot of the range of surface CAPE associated with non-derecho and derecho producing MCSs. Box and whisker plot of surface CAPE with each proximity sounding.

Statistical analysis of surface CAPE continues by bootstrapping the datasets (*n*=1000) in order to estimate the distribution of the sample mean. Confidence intervals

(95%) are created using the bootstrapped datasets, and it is clear that the medians of both datasets fall within the 95% confidence intervals of each other (Table 3.1). This suggests that the two datasets are similar, with no statistically significant difference between the two ($p < 0.05$). A permutation test ($n = 1000$) was also computed to resample the data and confirm the datasets are similar, resulting in a value near 0.30. This value represents the *p*-value, which is higher than the rejection threshold of $\alpha=0.05$. As a result the hypothesis that the datasets are similar cannot be rejected. This confirms that non-derecho producing MCSs and derecho producing MCSs occur in environments that are thermodynamically similar; therefore thermodynamic variables do not need to be considered for the prediction of derecho producing MCSs.

Table 3.1 Confidence Intervals of Surface CAPE

	Non-derecho Producing	**Derecho Producing**
97.5 percentile	**3442 J kg^{-1}**	**3595 J kg^{-1}**
Median	**2930 J kg^{-1}**	**3254 J kg^{-1}**
2.5 percentile	**2457 J kg^{-1}**	**2948 J kg^{-1}**

Confidence intervals are computed using the bootstrapped mean of the non-derecho producing and derecho-producing surface CAPE datasets.

After verifying that there is sufficient instability in place through analysis of CAPE, the kinematic variables should provide some insight on derecho event discrimination. Box and whisker plots are made separating derecho cases from non-derecho cases (Figure 3.2). Beginning with the magnitude of the wind shear vector from 0-6 km AGL, the derecho cases had a mean of 17.0 m s^{-1} while the non-derecho cases had a mean of 13.0 m s^{-1}. Although there is a 4 m s^{-1} separation between the means, there is still noticeable overlap of the two interquartile ranges (25^{th} to 75^{th} percentile) in the box and whisker plot, with the median of derecho cases falling within the interquartile range of non-derecho cases (and vice-versa). As a result, it appears that modeled deep layer wind shear alone is not able to discriminate between derecho formation as well as observational studies indicated. Furthermore, modeled deep layer wind shear values are generally higher compared to the observational Evans and Doswell (2001) study.

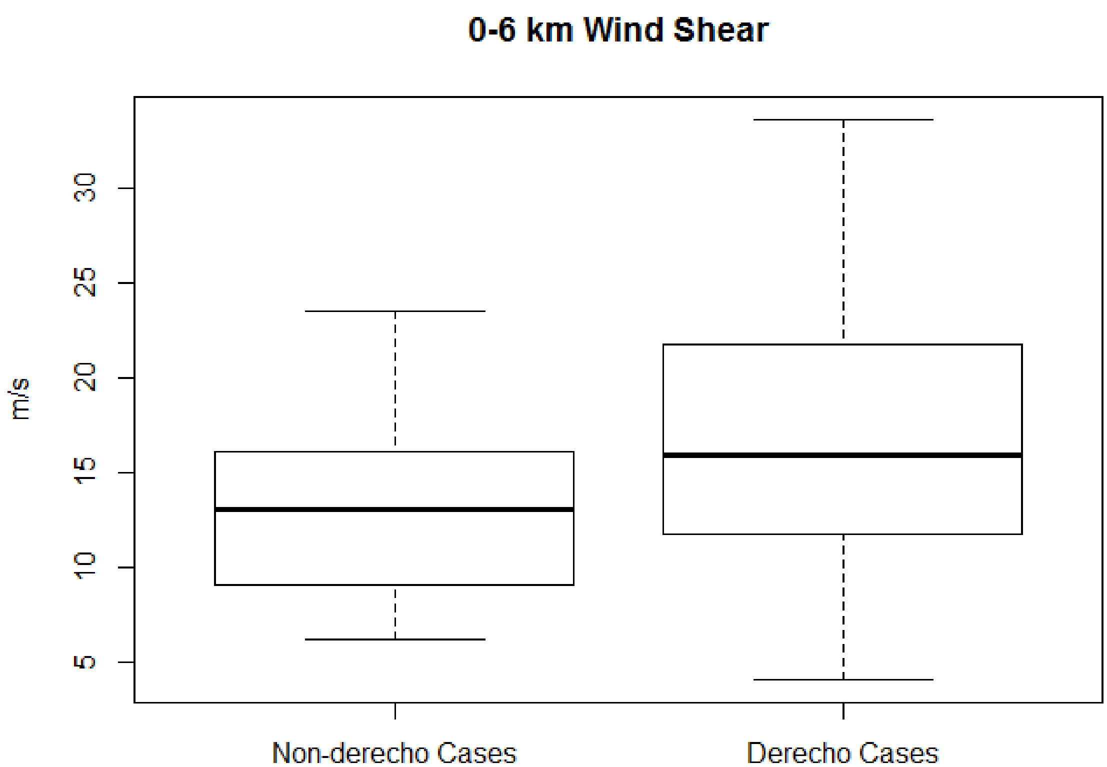

Figure 3.2 0-6 km Wind Shear Box Plot

Plot of the range of 0-6 km wind shear associated with non-derecho and derecho producing MCSs. Box and whisker plot of 0-6 km wind shear with each proximity sounding.

The wind shear datasets are bootstrapped (n=1000) to estimate the distribution of the sample mean. Confidence intervals (95%) are created using the bootstrapped datasets, and the medians of both datasets fall outside of the 95% confidence intervals of each other (Table 3.2). This indicates that the differences in the datasets are statistically significant ($p < 0.05$, which means the hypothesis that the datasets are similar must be rejected. Similarly, a permutation test (n=1000) resulted in a value near 0.015, which is less than our rejection threshold of α=0.05. As a result the hypothesis that the datasets are similar must be rejected. This test is in agreement that the differences in the datasets are statistically significant.

Table 3.2 Confidence Intervals of 0-6 km Wind Shear

	Non-derecho Producing	**Derecho Producing**
97.5 percentile	**15.0 m s^{-1}**	**18.8 m s^{-1}**
Median	**13.0 m s^{-1}**	**17.0 m s^{-1}**
2.5 percentile	**11.2 m s^{-1}**	**15.1 m s^{-1}**

Confidence intervals are computed using the bootstrapped mean of the non-derecho producing and derecho-producing 0-6 km AGL wind shear datasets.

The next and final kinematic variable analyzed is the magnitude of the mean wind vector from 0-6 km AGL. Box and whisker plots are made separating derecho cases from non-derecho cases (Figure 3.3). This variable immediately appears to have much better separation than the deep layer shear vector. The mean of the derecho cases is 11.7 m s^{-1}, while the mean of the non-derecho cases is 7.4 m s^{-1}. Although there is a similar quantity range separating the averages of both deep layer shear and deep layer mean wind, there is larger separation of the interquartile ranges (25^{th} to 75^{th} percentile) with the median of the derecho cases falling outside of the interquartile range of non-derecho cases (and vice-versa). In fact, there is complete separation between the interquartile ranges, with a 1st quartile value of 8.4 m s^{-1} in the non-derecho cases and a 3rd quartile value of 8.5 m s^{-1} in the derecho cases. It is worth noting that similarly with deep layer wind shear, the deep mean wind values are slightly larger overall than their observational Evans and Doswell (2001) counterparts. However, the deep mean wind in the observational study also had interquartile range (25th to 75th percentile) separation between the derecho and non-derecho cases, which may imply similar significance in discrimination (Evans and Doswell 2001).

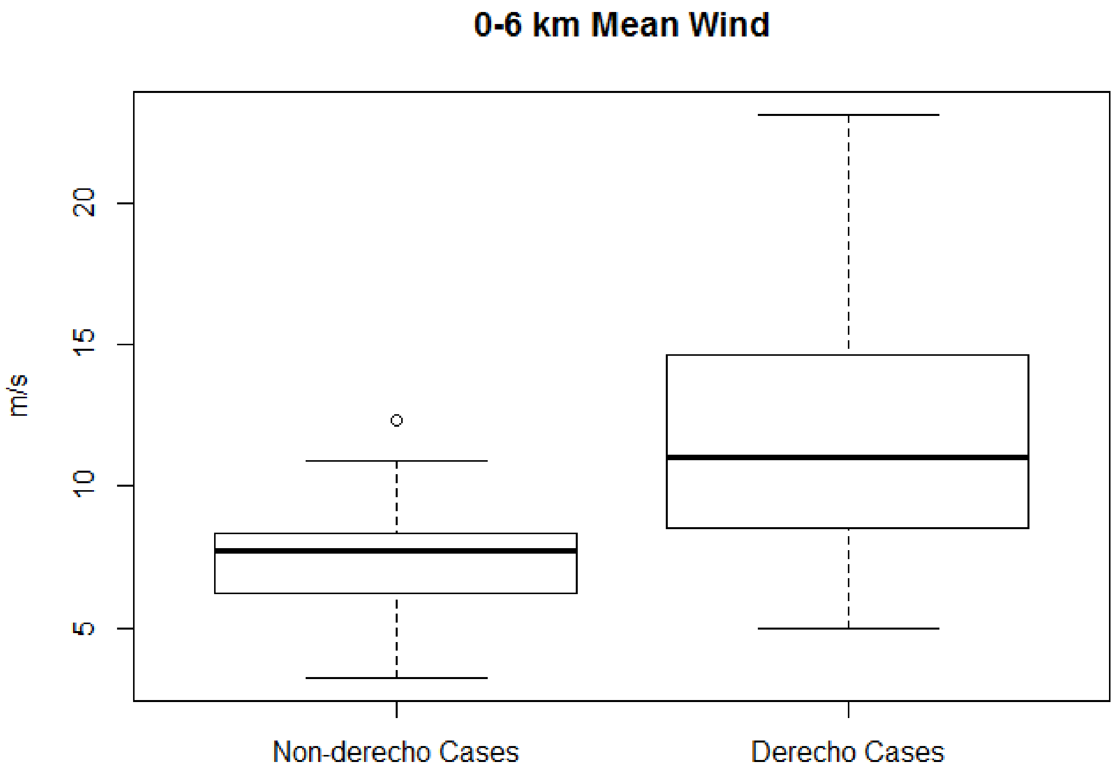

Figure 3.3 0-6 km Mean Wind Box Plot

Plot of the range of 0-6 km mean wind associated with non-derecho and derecho producing MCSs. Box and whisker plot of 0-6 km mean wind with each proximity sounding

The mean wind datasets are bootstrapped (*n*=1000) to estimate the distribution of the sample mean. Confidence intervals (95%) are created using the bootstrapped datasets, and the medians of both datasets fall outside of the 95% confidence intervals of each other (Table 3.3). This indicates that the differences in the datasets are statistically significant ($p < 0.05$), which means the hypothesis that the datasets are similar must be rejected. Similarly, a permutation test (*n*=1000) resulted in a value near 0.00, which is less than our rejection threshold of α=0.05. As a result the hypothesis that the datasets are similar must be rejected. This test is in agreement that the differences in the datasets are statistically significant.

Table 3.3 Confidence Intervals of 0-6 km Mean Wind

	Non-derecho Producing	**Derecho Producing**
97.5 percentile	**8.4 m s^{-1}**	**12.9 m s^{-1}**
Median	**7.4 m s^{-1}**	**11.7 m s^{-1}**
2.5 percentile	**6.4 m s^{-1}**	**10.6 m s^{-1}**

Confidence intervals are computed using the bootstrapped mean of the non-derecho producing and derecho-producing 0-6 km AGL mean wind datasets.

Contingency Table Analysis

Contingency tables for derecho formation are tabulated based on discriminatory values used in the DCP equation (Coniglio et al. 2005). This corresponds to a discriminatory value of 10.3 m s^{-1} for deep layer wind shear and 8.2 m s^{-1} for deep layer mean wind. The results indicate a 72.7% probability of detection (POD) based on simulated deep layer wind shear and an 84.8% POD based on simulated deep layer mean wind. For false alarm rate (FAR) the results indicate 13.0% and 15.2% respectively. This corresponds to a proportion correct (PC) of 69.6% and 79.7% respectively. Finally the Heidke skill score (HSS) provides a measure of success of the forecast relative to what it would be by chance, with a deep layer shear value of 0.24 and a deep layer mean wind value of 0.54. This indicates that the deep layer mean wind is more than twice as successful as deep layer wind shear at forecasting derecho formation using simulated sounding data relative to what it would be by chance. Therefore there is consensus within the contingency statistics that simulated environmental deep layer mean wind is the best single predictor for derecho formation, with simulated environmental deep layer wind shear also capable of statistically significant discrimination. Brier scores are another way to determine how well the discriminatory model performs, with a score of 0.30 for deep layer wind shear and 0.20 for deep layer mean wind (lower number is better). Additionally the Brier skill score computed, incorporating "climatology", by factoring in the binary nature of the prediction (derecho either did or did not occur). The resulting Brier skill scores are 0.39 and 0.59, respectively (higher number is better). These Brier statistics are in agreement with the contingency statistics that deep layer mean wind is a better predictor than deep layer wind shear.

Table 3.4 Contingency Table for 0-6 km Wind Shear

	Derecho Occurred	**Derecho Did Not Occur**
Derecho Predicted	**40**	**15**
Derecho Not Predicted	**6**	**8**

Contingency table for 0-6 km AGL wind shear vector magnitudes with a discriminatory threshold of 10.3 m s^{-1} as established by Evans and Doswell 2001 (3^{rd} quantile of non-derecho producing cases).

Table 3.5 Contingency Table for 0-6 km Mean Wind

	Derecho Occurred	**Derecho Did not Occur**
Derecho Predicted	**39**	**7**
Derecho Not Predicted	**7**	**16**

Contingency table for 0-6 km AGL mean wind magnitudes with a discriminatory threshold of 8.2 m s^{-1} as established by Evans and Doswell 2001 (3^{rd} quantile of non-derecho producing cases).

Discrimination of Derecho Severity

Now that statistical significance in the discrimination of derecho formation has been shown, attention can be shifted towards discrimination of relative derecho severity. Kinematic variables (deep layer wind shear and deep layer mean wind) are examined after making box and whisker plots separating low-end, moderate, and high-end derecho cases (Figures 3.4 and 3.5). Both deep layer wind shear and deep layer wind show increasing values of the median with respect to intensity (low-end, moderate, and high-end). The low-end cases have the smallest median values (14.3 m s^{-1} and 20.7 m s^{-1} for deep layer shear and deep layer mean wind, respectively) and high-end events have the largest median values (9.9 m s^{-1} and 12.1 m s^{-1}, respectively). However, since there is substantial overlap between all of the interquartile ranges (25^{th} to 75^{th} percentile), it does not appear likely that there will be similar skill in predicting relative derecho severity (compared to discrimination of derecho formation) only based on environmental kinematic variables. It is worth noting that formation of moderate and especially high-end derecho events are even more likely to be accurately predicted by the model. For example, all 10 proximity soundings for high-end events exhibited deep layer mean wind values of over 8.2 m s^{-1}, indicating a 100% probability of detection for these cases based on formation, therefore, it is more likely that the model will predict high-impact events where predictive value is most beneficial.

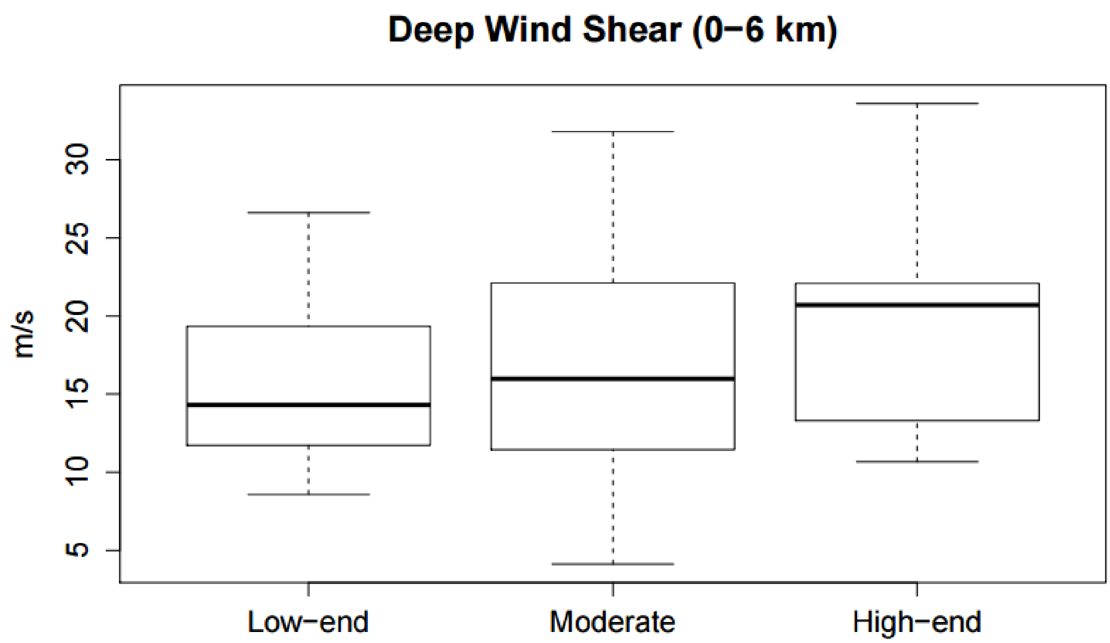

Figure 3.4 Deep Wind Shear Derecho Severity Box Plot

Plot of the range of 0-6 km AGL wind shear associated with low-end, moderate, and high-end derecho producing MCSs.

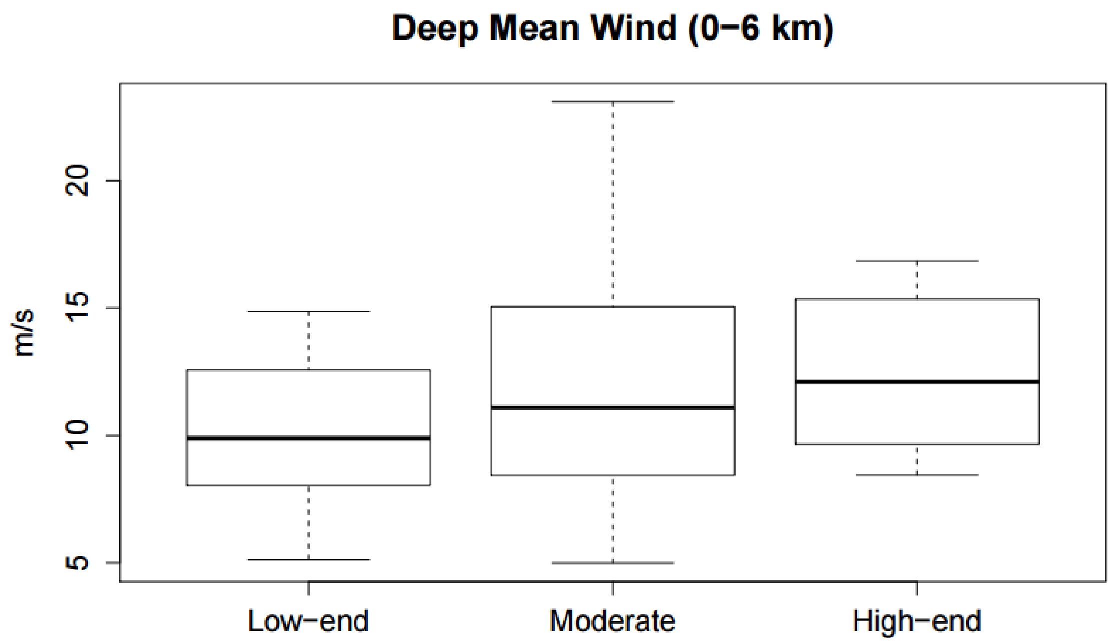

Figure 3.5 Deep Mean Wind Derecho Severity Box Plot

Plot of the range of 0-6 km AGL mean wind associated with low-end, moderate, and high-end derecho producing MCSs

CHAPTER IV

CONCLUSIONS

Although progressive derecho formation has been extensively researched in observational studies and highly specialized weather model simulations alike, there has not been much work done on using observational and simulated data in tandem for predictive purposes. While observational studies of environmental kinematic variables (deep layer wind shear and deep layer mean wind) have been shown to discriminate well between warm-season derecho formations; this study attempts to verify these results within the context of numerical weather prediction by running a similar number of cases (25 derecho producing, 25 non-derecho producing) within a specialized high-resolution WRF configuration. 69 total modeled proximity soundings were derived from 44 of the 50 total cases, with six of the non-derecho cases not being used due to insufficient criteria for a proximity sounding. Discriminatory analysis is conducted by separating the modeled proximity soundings based on whether the parent MCS was a derecho producing case or non-derecho producing case. The results suggest that the high-resolution (4x4 km) WRF model is able to accurately simulate the environment of warm-season MCSs, with statistically significant success in discrimination of formation using only environmental kinematic variables (wind shear and mean wind). Furthermore, after testing the predictability of derecho formation using observational thresholds of the derecho composite parameter, it is confirmed that the model performs well with a majority of cases predicted correctly using both kinematic variables. Relevant contingency statistics include a 72.7% POD using deep layer wind shear and an 84.8% POD using deep layer mean wind, 13.0 % FAR for wind shear and 15.2% FAR for mean wind, and 69.9% PC and 79.7% PC respectively. This portion of the study completes the main project objective of verifying that WRF model framework can predict the environment associated with derecho-producing MCSs or non-derecho producing MCSs. Further separating the derecho-producing MCS cases into relative severity (low-end, moderate, and high-end) provided additional insight into the significance of the environmental kinematic variables. While the same level of discrimination is likely not possible using the relative derecho severities, it is clear that the median values of wind shear and mean wind increase with respect to relative severity. This suggests that discrimination of the formation of derechos is even more accurate when concerned with the highest impact events. In the case of this particular study, using the environmental mean wind alone correctly predicted all cases of high-end derecho producing MCSs.

While this study confirmed the findings of observational studies within the context of a high-resolution numerical weather prediction framework, future studies can explore a more dynamic method of recording kinematic variables, both spatially and temporally. This would allow for better interrogation of the discriminatory kinematic variables that are used for prediction, as this study only used explicitly defined points in space and time based on observational limitations. For example, taking the highest value directly ahead of the leading edge of the bow echo rather than fixed points at sounding locations, and recording these values at an hourly or half-hourly interval rather than only 0000 UTC or 1200 UTC would dramatically increase the amount of data that can be used.

By making better use of all of the available data produced by the model it is expected that further refinement of kinematic discriminatory variables is possible. Although these more precise methods of data collection are not currently practical within the context of observational studies, numerical weather prediction has the ability to utilize very large quantities of data to further understand and improve derecho formation and intensity forecasts. This, combined with a larger number of derecho and non-derecho producing cases, could result in further improvements as well. These same methods can be expanded to further examine the relationship of derecho severity as well.

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APPENDIX A

LIST OF EVENTS

Run	Event	Reports	Class	Start Date	Start Time	Start Lat	Start Lon	End Date	End Time	End Lat	End Lon	Duration
1	126	110	high-end	970621	0230	41.75	-96.88	970621	1139	42.6	-90.02	9.1
2	207	78	high-end	000529	2349	41.55	-101.72	000530	0547	41.1	-95.85	6
3	161	93	high-end	980627	2125	43.63	-95	980628	0534	42.7	-88.55	8.1
4	153	240	high-end	980618	1840	41.07	-94.37	980619	0800	41.9	-83.4	13.6
5	146	266	high-end	980531	0115	44.57	-96.88	980531	1203	42.5	-82.87	10.9
6	163	214	high-end	980629	1525	42.62	-97.87	980630	0404	38	-84.18	12.8
7	108	94	high-end	960519	0440	44.27	-96.13	960519	0930	45.2	-89.15	4.9
8	128	79	high-end	970701	2030	44.58	-97.2	970702	0740	44.7	-88.88	11.1
9	209	63	low-end	000601	1948	44.45	-90.83	000602	0445	42.9	-83.28	9
10	80	22	low-end	950516	1310	37.97	-90.12	950516	2145	35.2	-84.88	8.4
11	78	55	low-end	950514	0700	36.58	-88.62	950514	1330	35.5	-83	6.3
12	83	62	low-end	950607	1125	40.42	-95.52	950608	0115	36.1	-87.07	13.9
13	140	34	low-end	980520	0119	41.42	-102.37	980520	1055	41.5	-93.67	9.4
14	212	42	low-end	000710	0251	43.18	-95.87	000710	1010	43.1	-89.42	7.6
15	141	56	low-end	980520	1818	38.08	-88.17	980521	0134	37.3	-81.78	7.2
16	129	59	low-end	970702	1952	40.83	-84.93	970703	0715	35.9	-81.55	11.6
17	203	107	moderate	000509	1937	38.63	-88.95	000510	0146	42.7	-82.57	6.1
18	151	173	moderate	980612	2004	41.22	-86.78	980613	0646	37.8	-81.22	10.4
19	144	107	moderate	980528	2158	42.52	-93.27	980529	0818	43.3	-83.08	10.6
20	139	83	moderate	980515	1616	41.08	-96.13	980516	0223	44.5	-89.57	10.1
21	112	120	moderate	960807	0001	43.75	-96.9	960807	1104	43.8	-88.02	11
22	234	68	moderate	010609	2349	44.05	-103.05	010610	0712	43.4	-95.13	7.6
23	155	29	moderate	980622	0319	39.07	-101.25	980622	1200	38.8	-93.75	8.8
24	143	51	moderate	980521	2234	42.02	-97.42	980522	1121	38.4	-88.93	12.9
25	237	111	moderate	010708	1549	39.62	-86.25	010708	2325	35	-82.18	7.8

26	1-N	61	non-derecho	950708	1200	39	-94	950709	1200	35	-90	12
27	2-N	50	non-derecho	950805	1200	40	-100	950806	1200	40	-97	12
28	3-N	44	non-derecho	950810	1800	45	-100	950811	1800	45	-95	12
29	4-N	7	non-derecho	960515	1800	42	-102	960516	1800	41	-98	12
30	5-N	27	non-derecho	960522	1800	40	-102	960523	1800	40	-96	12
31	6-N	49	non-derecho	960525	1200	39	-93	960526	1200	37	-88	12
32	7-N	58	non-derecho	960620	1800	42	-98	960621	1800	41	-95	12
33	8-N	92	non-derecho	960621	1800	37	-102	960622	1800	38	-98	12
34	9-N	72	non-derecho	970611	1800	41	-100	970612	1800	40	-95	12
35	10-N	64	non-derecho	980706	1200	43	-99	980707	1200	42	-94	12
36	11-N	64	non-derecho	990607	1800	43	-100	990607	1800	44	-97	12
37	12-N	37	non-derecho	990701	1800	43	-99	990702	1800	41	-95	12
38	13-N	34	non-derecho	990719	1800	41	-104	990720	1800	41	-100	12
39	14-N	13	non-derecho	990806	1200	41	-96	990807	1200	41	-96	12
40	15-N	39	non-derecho	990807	1800	38	-97	990808	1800	38	-93	12
41	16-N	12	non-derecho	000515	1800	45	-98	000516	1800	43	-96	12
42	17-N	35	non-derecho	000603	1200	45	-98	000604	1200	43	-96	12
43	18-N	46	non-derecho	000629	1200	42	-101	000630	1200	38	-98	12
44	19-N	74	non-derecho	000705	1200	42	-95	000706	1200	41	-92	12
45	20-N	84	non-derecho	000716	1800	39	-98	000717	1800	37	-97	12
46	21-N	59	non-derecho	000718	1800	39	-102	000719	1800	39	-99	12

47	22-N	74	non-derecho	000726	1800	40	-95	000727	1800	38	-95	12
48	23-N	68	non-derecho	000801	1800	44	-104	000802	1800	43	-103	12
49	24-N	66	non-derecho	000804	1800	45	-100	000805	1800	44	-97	12
50	25-N	50	non-derecho	0010617	1800	40	-99	00010618	1800	41	-96	12