Chapter 4

A Case Study of Atmospheric Dynamics and Thermodynamics in Derechos and the Societal Impacts

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Additional information is available at the end of the chapter

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Abstract

The word "derecho" is used to differentiate a storm having straight-line winds as opposed to rotational, tornadic winds. Although the term "derecho" is relatively old, derechos were not readily recognized by the general public until recent outbreaks caused significant widespread damage and associated fatalities. Most notably, the 2012 Mid-Atlantic Derecho in the USA brought these types of storms to the public's attention as a variety of societal impacts including infrastructural damage, power outages, and fatalities occurred over an extensive area from outside of Chicago to Washington, DC The associated damage can be more widespread than tornadoes, and the number of fatalities is comparable to those found in medium-intensity tornadoes.

This study investigated the importance of the dynamics and thermodynamics in maintaining the intensity of derechos. Key meteorological parameters were measured over six stations where the 2012 Mid-Atlantic Derecho passed. Low- to mid-level wind shear, as well as the Convective Available Potential Energy (CAPE) and Most Unstable Convective Available Potential Energy (MUCAPE), was found to be significantly higher at the time of passage, which allowed the system to intensify and propagate down-stream.

Keywords: derechos, dynamics, thermodynamics, convection, societal impacts

1. Introduction

North America is known for its many types of atmospheric hazards including tornadoes, thunderstorms, blizzards, and hurricanes. Physical geography plays a pivotal role as two mountain ranges, the Rockies in the west and the Appalachians in the east, are both oriented north-south. Since there is no physical barrier to prevent cold air masses to the north and warm air masses to the south from interacting with each other, severe and hazardous weather is commonly produced. The warm, moist air is easily lifted by the colder, drier air producing mid-latitude storms like no other place on Earth. In fact, North America generates almost 75% of all known tornadoes [1].

However, there is another type of atmospheric hazard that does not rotate violently but nevertheless can cause considerable damage and a variety of societal impacts—the *derecho*. The term "derecho" is not as commonly known as "tornado" but has been around for many years. Derecho was first used by a University of Iowa physics professor, Dr. Gustavus Hinrichs, in 1888 to describe a thunderstorm that produced strong straight-line winds as opposed to rotational winds [2]. Hinrichs believed another term was needed to differentiate violent straight-line storms from tornadoes; therefore, he used "derecho," which is Spanish for "straight ahead." However, the word "derecho" was virtually absent from the meteorological lexicon for almost 100 years until the 1980s when Robert Johns and William Hirt [3] re-introduced the term. Although, not as widely known as tornadoes by the general public, derechos are gaining recognition for their destructive capability [4]. Even though derechos can form anywhere around the world, they predominantly form in the USA. In fact, very few studies have even been published about derechos occurring outside North America [5, 6]. Therefore, the focus of this study will be on the USA and a particularly strong derecho in 2012.

2. Background

Derechos have been specifically defined as "families of downburst clusters" that originate from a mesoscale convective system while covering an area where the major axis is at least 400 km [3, 7, 8]. They are associated with causing straight-line, non-tornadic damage and occur most frequently during the summer months, especially east of the Rocky Mountains in the USA [3, 9]. In addition, areas of convection produce "bow echoes" [10] that propagate downstream and can create severe downbursts.

2.1. Types of derechos

Derechos are often divided into four different types: progressive, serial, hybrid, and low-dew point (dry). Regardless of the type, derechos often form from a mesoscale convective system where the individual thunderstorms often start to replicate as they propagate downstream.

Progressive derechos are often found along a stationary frontal boundary oriented west-east with mid-level winds flowing parallel (west-east) to the frontal boundary [3, 11]. With sufficient convection, a mesoscale convective system will develop along the boundary evidenced by a bow echo typically having a length of up to 250 miles in the beginning phases. As the system travels downstream, a sharp downdraft of cold air intensifies near the center of the bow echo and is pushed further ahead by the west-east mid-level wind flow. The size of the derecho often increases to lengths greater than 250 miles. Progressives are more common during the summer as they require more convection at the site of the frontal boundary.

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Serial derechos similarly form along a west-east stationary frontal boundary; however, the mid-level winds are more from a southerly direction [3]. This results in multiple bow echoes that are smaller than the progressive counterparts, but are often embedded in a larger mid-latitude low pressure system. Since serial derechos are often associated with warm southerly flow from the low-level jet aiding the convection, these can even be observed during the spring and fall.

There are circumstances where the derecho will take on properties of both, making it a "*hybrid*." These are often found when there is a low-pressure system present (as found in serial derechos) but there is also a west-east mid-level flow that is parallel to the stationary frontal boundary similar to those found in progressives. As a result, multiple derechos of both types can be found in the system [3].

Dry or *low-dew point* derechos are found in environments of low moisture where the dew points are typically low (i.e., dew points lower than 60°F (16°C)). These types of environments are often found in the spring or fall in the Central Plains of the USA or in the Rocky Mountain states throughout the year. They take on characteristics similar to dry microbursts as cold, dry air rapidly accelerates toward the surface.

2.2. Climatology

As North America is the most favorable location for tornadoes due to the interaction of warm, moist air with cold, dry air, the same is true for derechos. They are typically found east of the Rocky Mountains, with favored areas centered on the Upper Mississippi and Ohio River Valleys [3]. The climatological averages range from one derecho per year in the Mississippi and Ohio River Valleys to about one every four years near the Rocky Mountains and Atlantic Coast. The most likely time for formation is during the warm season primarily during the months of May, June, and July [3].

Bentley and Mote [9] found similar results for the timing of derechos, in that they primarily form during the warm season, however, the authors note they are more likely to form farther south in the southern Great Plains. In contrast to previous studies, they found the favored area is centered near Oklahoma and extended north-eastward with a secondary maximum in the upper Ohio River Valley near Pennsylvania. They noted that the earlier study by Johns and Hirt used derecho events from a year that had an unusually high number in the Upper Midwest. When the inflated year was factored out, the resulting maximum shifted southward into the southern Great Plains.

Other studies, including Bentley and Sparks [12], have showed that the conditions favorable for derechos fluctuate from year to year, causing the frequency to shift along the Mississippi River Valley. Regardless, there appears to be a favorable axis oriented north-south along the Mississippi River extending into the southern Great Plains. During the cold season, bow echoes were much more likely to form in the southeastern USA, especially when there is a strong, warm southwestern flow [13]. The resulting southwesterly flow through all levels is responsible for primarily producing serial derechos.

2.3. Societal impacts

The societal impacts from derechos have been anticipated to grow as a result of population growth and increased urbanization [14]. Derecho impacts are thought to be as dangerous as tornadoes and hurricanes since they cover large areas and occur relatively frequently. Injuries and fatalities are the most obvious impacts and are expected where the frequency is high. However, a study by Ashley and Mote [4], found that an unusually high percentage of fatalities occurred in areas where the frequency of derecho events is not necessarily the highest. It was theorized that perhaps these regions had poorer warning systems in place as well as less awareness by the general public, thereby increasing the vulnerability. Some regions have been suggested, such as the upper Midwest and Great Lakes, to be susceptible to intense, warm season progressive derechos.

Most derecho fatalities occurred in vehicle accidents either by the vehicle overturning, a tree falling onto the vehicle, or the vehicle crashing into a fallen tree [4]. They also found fatalities were common on the open water in the form of drownings since boats can be easily overturned from the strong winds. As for injuries, most were again vehicle related. But also many injuries are the result of people being in poorly built structures such as mobile homes and being struck by flying debris.

When compared with other severe weather systems such as tornadoes and hurricanes, derecho fatalities are comparable [4]. In fact, derecho fatalities were found to be more than those caused by EF0 and EF1 tornadoes. Only when EF2 tornadoes were added did the totals surpass the derecho fatalities. Hurricane fatalities were found to be more than derechos, however, simply because the causes of death can come from a variety of factors including inland flooding, tornadoes, and storm surge.

In addition, insured losses from US derechos found that the estimated damage was often greater than $100 million for each outbreak [4]. Brooks and Doswell [15] noted the amount of estimated damage is very comparable to most tornado outbreaks and smaller land-falling hurricanes. Due to uninsured property and lack of derecho damage reports, the amount of damage, however, is apt to be even greater than described.

There have been several notable derecho events (averaging one per year) in the USA, specifically during the 1998 warm season that brought three derechos and extremely hot temperatures to many areas of the country. More recently, during the summer of 2012, which also brought extremely hot summertime temperatures, the great Mid-Atlantic Derecho occurred. The large 2012 derecho originated just outside of Chicago early in the morning and propagated swiftly toward Washington, DC, later that evening. Over five million customers in the region lost their power for more than a week and 22 fatalities were reported [16]. **Figure 1** shows an image before (top) and after (bottom) the storm. Notice the reduced number of lights in the bottom image around major metropolitans such as Columbus, OH, Pittsburgh, PA, and Washington, DC, depicting the loss of power. Not only did the storm adversely affect people throughout the region, but even people travelling around the region were impacted. The Mid-Atlantic contains large metropolitan areas; therefore, air and land travel is extremely abundant. Airplanes had to be diverted around the storm entering and leaving major airports, while

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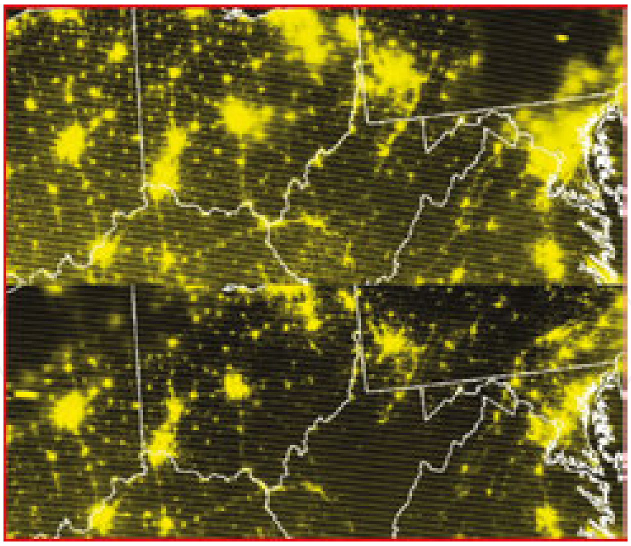

Figure 1. Before (top) and after (bottom) of the lights in the Mid-Atlantic depicting the power outages (Courtesy of CIMSS, University of Wisconsin).

gasoline was scarce in certain areas due to the power outages. Even local National Weather Service offices had difficulty sending reports due to the widespread power outages. **Figure 2** shows the official storm reports from the June 29, 2012, outbreak; however, there is a data "hole" in the middle of the plot of reports since electricity went out at a local National Weather Service office and regional cellular communication towers were down so reports could not be sent.

Coupled with the brutally hot temperatures (often near 100°F (38°C)), the negative societal impacts made the general public of the USA painfully aware of derechos. In fact, many people had never heard of the term before this powerful event. However, after showing the millions of dollars of damage, news media outlets made sure "derecho" was the new buzzword for the year of 2012 by broadcasting segments entitled, "What is a derecho?" [17, 18] and brought the term back into the meteorological lexicon.

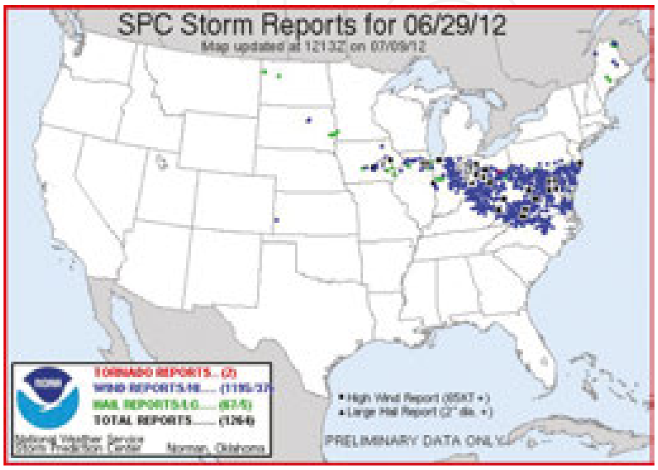

Figure 2. Storm reports depicting the data "hole" in Central West Virginia (Courtesy of NWS/SPC).

3. Case study: 2012 Mid-Atlantic Derecho

The June 29, 2012, Mid-Atlantic Derecho was one of the most destructive weather events of the year and will be remembered as one of the most intensive storms in the region. The event was responsible for 22 deaths, widespread infrastructural damage estimated at over $1 billion, and approximately 5 million people losing power [16]. Two general types of derechos exist: serial, which is produced by multiple bow echoes embedded within a larger squall line; and progressive that originates as a small, single bow echo but develops into a large bow echo system hundreds of miles long. The dynamic and thermodynamic environmental conditions ultimately determine the type of derecho that develops. The 2012 Mid-Atlantic Derecho exhibited the characteristics of a progressive derecho as it originated near a quasi-stationary boundary in Iowa. The derecho quickly propagated into a small bow echo near Chicago (**Figure 3**) and then raced east expanding in size as it reached the Mid-Atlantic coast.

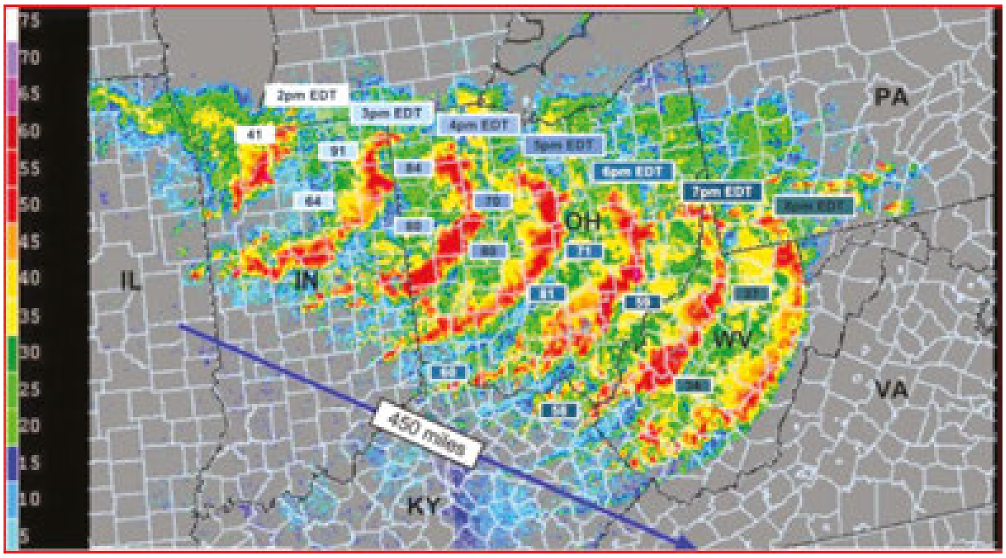

Figure 3. Radar Base Reflectivity overlay of the derecho progression June 29, 2012. Overlay courtesy of G. Carbin NWS/Storm Prediction Center.

Since the formation of derechos is dependent on the thunderstorms replicating in a downwind manner, atmospheric conditions must be examined to determine if the individual thunderstorms will develop sequentially. However, progressive derechos remain difficult to forecast largely because of the sub-grid scale interactions between the individual thunderstorms with the environment [19]. It has been shown that progressive derechos often form during the warm season and develop in a variety of shear and instability conditions [20, 21]. Derechos typically develop when the mid-level shear is weak while the low-level shear is strong. In addition, derechos form in very unstable environments indicated by high values of Convective Available Potential Energy (CAPE) greater than 1500 J Kg^{-1}. On the other hand, they have been shown to form in low CAPE environments (less than 500 J kg^{-1}) if the synoptic forcing is high [21, 22]. The objective of this study is to investigate the dynamic and thermodynamic factors responsible for the 2012 outbreak and determine if those parameters during the event were signifi-

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cantly different from the mean values. As a result, the parameters can be examined to see if they are outside the generally accepted thresholds for forecasting derechos.

3.1. Methodology

Data were collected from the North American Mesoscale (NAM) model for the 1200 UTC, 1800 UTC (June 29, 2012), and 0000 UTC (June 30, 2012) runs. Six stations were selected for closer investigation (Davenport, Iowa; Chicago, Illinois; Ft. Wayne, Indiana; Wilmington, Ohio; Charleston, West Virginia; and Washington, DC) due to their proximity to the passage of the storm system. The relative station locations are shown in **Figure 4** as well as the time of the derecho passage is stated in **Table 1**. Radar images at the time of the storm passage are shown for each station in **Figure 5**.

Figure 4. USA Map with the six stations under investigation: (a) Davenport, IA; (b) Chicago, IL; (c) Ft. Wayne, IN; (d) Wilmington, OH; (e) Charleston, WV; (f) Washington, DC.

Station	Time of passage
A: Davenport, IA	1300 UTC 06/29/12
B: Chicago, IL	1600 UTC 06/29/12
C: Ft. Wayne, IN	1800 UTC 06/29/12
D: Wilmington, OH	2100 UTC 06/29/12
E: Charleston, WV	2300 UTC 06/29/12
F: Washington, DC, Dulles Airport	0200 UTC 06/30/12

Table 1. Six stations used in the study and the time of derecho passage.

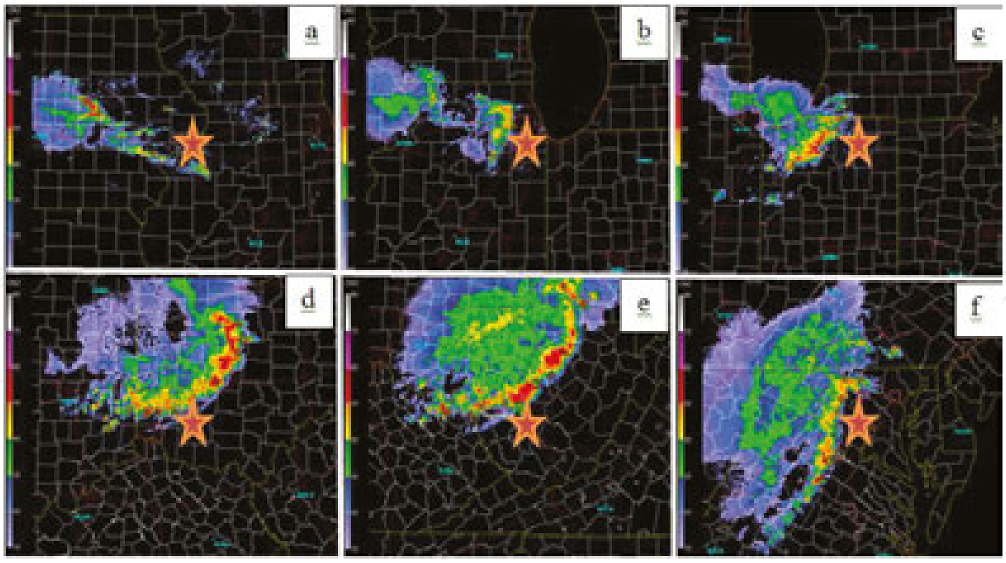

Figure 5. Base Reflectivity Radar Imagery of the derecho as it was passing through the six stations investigated in the study (indicated by star): (a) Davenport, IA; (b) Chicago, IL; (c) Ft. Wayne, IN; (d) Wilmington, OH; (e) Charleston, WV; (f) Washington, DC, Dulles International Airport.

Parameter	Abbreviation	Units
Convective available Potential energy	CAPE	J kg^{-1}
Most unstable convective Available potential energy	MUCAPE	J kg^{-1}
Downdraft convective Available potential energy	DCAPE	J kg^{-1}
Precipitable water	PW	cm
Convective temperature	CT	°C
950 hPa–850 hPa lapse rate	Lapse rate	°C km^{-1}
Helicity	Helicity	m^2 s^{-2}
Bulk Richardson number	BRN	Unitless
1 km storm relative inflow	SR inflow	m s^{-1}
Wind shear (0–6 km)	Shr 0–6	m s^{-1}
Wind shear (0–3 km)	Shr 0–3	m s^{-1}
Wind shear (3–6 km)	Shr 3–6	m s^{-1}

Table 2. List of wind shear and instability parameters.

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Twelve parameters were collected in hourly intervals for all six stations beginning at 1200 UTC on June 29, 2012, until the time of the storm passage. The list of instability and wind shear parameters investigated are shown in **Table 2**. The instability parameters included the following: Convective Available Potential Energy (CAPE); the Most Unstable CAPE (MU-CAPE), the potential energy within the lowest 300 hPa; the Downdraft CAPE (DCAPE), measuring the strength of the rain-cooled downdraft; the 950–850 hPa lapse rate, describing lower-level instability; and convective temperature (CT), the surface temperature that must be attained for convection to occur. Precipitable water (PW) is the vertically integrated amount of water through the column of air. Wind shear parameters included the Bulk Richardson Number (BRN), which is a dimensionless ratio of turbulence versus wind shear. Helicity is a measure of the helical or "corkscrew" flow of the air. Additionally the 1 km storm relative inflow and three different layers of wind shear were included.

The model data were analyzed in BUFKIT [23], a visualization software designed for weather forecasting and analysis. The data were standardized by hour (…t-2, t-1, t) until the time of storm passage. Downshear Convective Available Potential Energy values were calculated by estimating the temperature of the downdraft parcel (T_{pd}), which is between the mid-level wet bulb potential temperature and the updraft wet bulb potential temperature [24] and is shown by the following equation:

$$\frac{1}{2} * g * \left(\frac{Te - Tpd}{Te}\right) * \Delta z \tag{1}$$

where T_e is the environmental surface temperature (K), T_{pd} is the expected parcel downdraft surface temperature (K), and Δz is the depth of the negatively buoyant air (m).

One-sample one-tailed *t*-tests were then conducted (for each station and each variable) at hourly intervals relative to the storm passage in order to determine if parameter values were significantly larger than the mean daily values and to potentially develop critical forecasting thresholds. The number of samples varied at each station since they were measured hourly starting at the beginning of the day until relative to the storm passage; therefore, more data were available progressing eastward. Level 2 Radar, which has higher resolution than conventional Level 3 Radar and offers dual polarmetric data [25] was also analyzed in addition to surface and upper air plots.

4. Results

A quasi-stationary (QS) boundary was oriented west-east from Iowa to the Mid-Atlantic region during the morning hours on June 29, 2012 (**Figure 6**). Close inspection of the soundings and surface plots revealed warm temperatures and high dew points in the region at 1500 UTC (**Figures 7** and **8**). On the northern side of the boundary, temperatures were in the mid-70s to the low-80s (Fahrenheit) (21–28°C), while dew points were around 60°F (16°C). However, on the southern side of the boundary, temperatures were in the mid-80s (30°C) to around 90°F (32°C), while the dew points were close to 70°F (21°C). The reason the air was unusually warm and humid in the morning hours was because it was the result of a decaying mesoscale convective system the previous day. A small region of convection then formed over northern Iowa as a strong southerly flow from the nocturnal low-level jet provided ample moisture to the system indicated by the dew point equaling the temperature around 900 hPa. The sounding at Davenport (**Figure 9**) at 1200 UTC exhibited a classic "inverted-v" shape confining the potential energy close to the surface and preventing thunderstorms from developing too quickly.

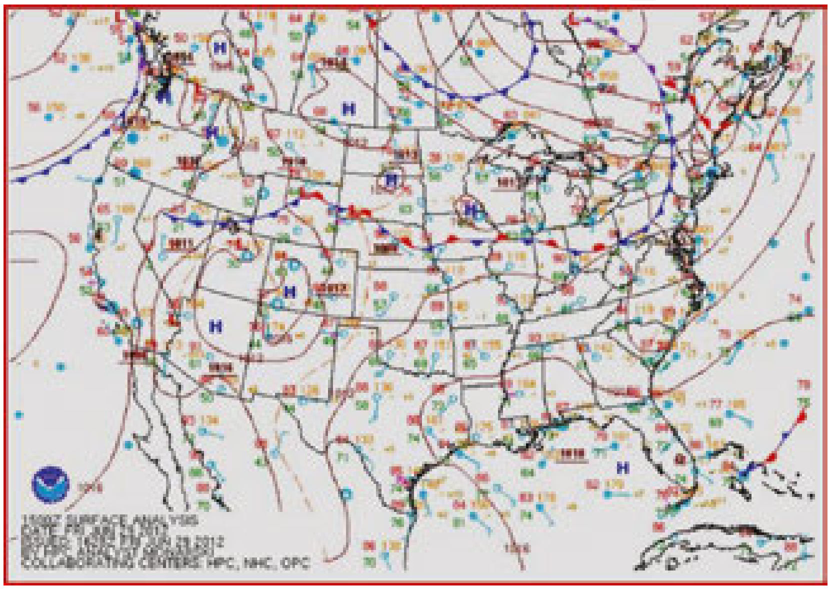
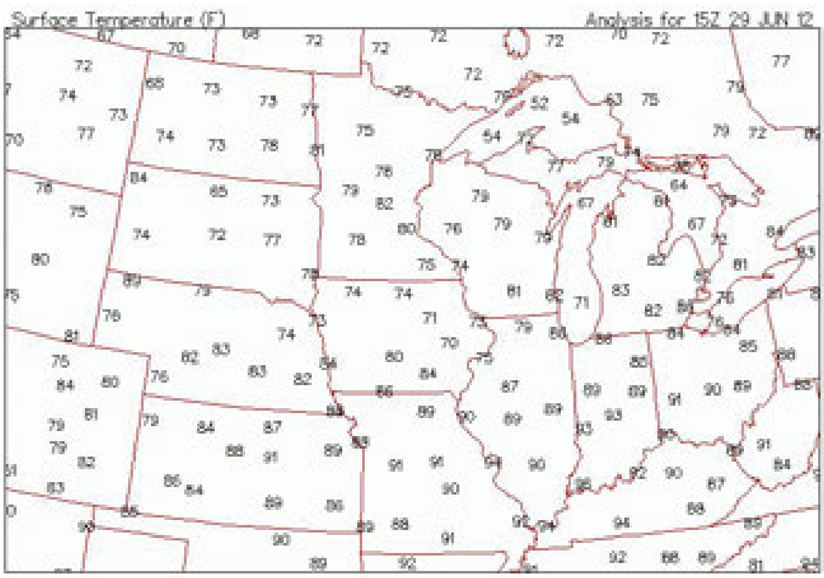


Figure 6. Surface map at 1500 UTC for June 29, 2012.



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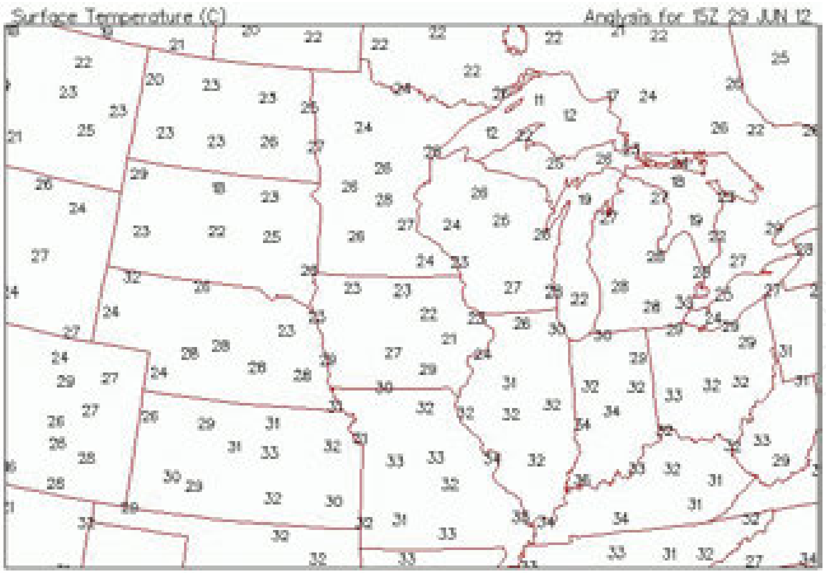

Figure 7. Surface plot of temperatures (a) (previous page °F); (b) (above °C) at 1500 UTC June 29, 2012.

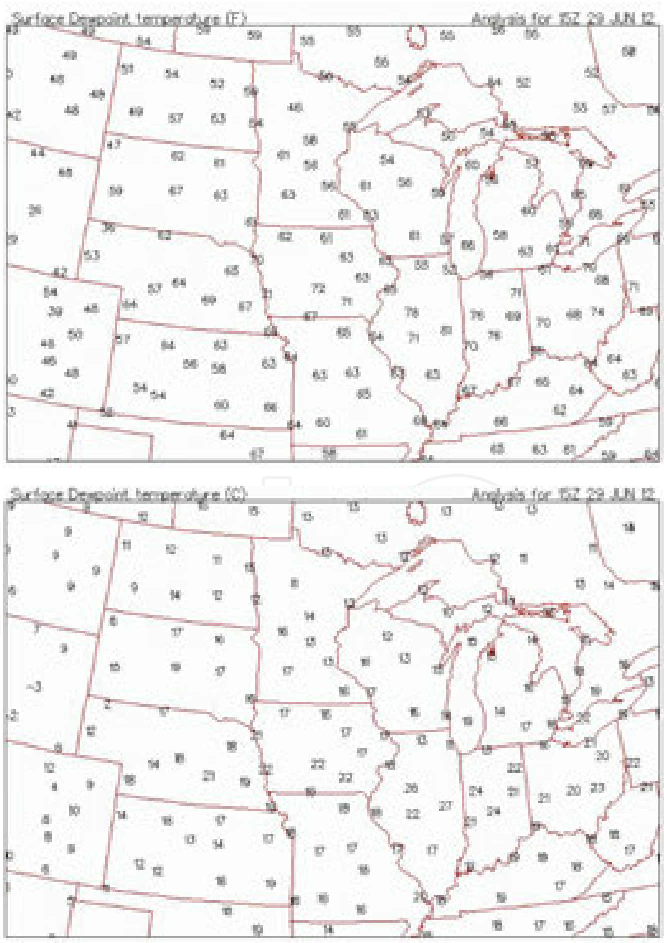

Figure 8. Surface plot of dew points (a) (top °F); (b) (bottom °C) at 1500 UTC for June 29, 2012.

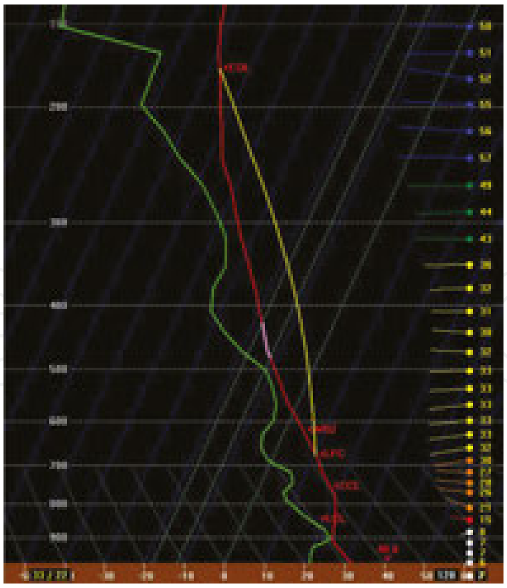

Figure 9. NAM 1200 UTC run for sounding at Davenport, IA for 1500 UTC, June 29, 2012.

A small of line of thunderstorms formed along the QS boundary and passed through Davenport, IA at approximately 1300 UTC. The 500 hPa chart did not show any short-wave troughs but exhibited strong westerly flow over northern Iowa (**Figure 10**). However, the 250 hPa chart showed a jet streak with the right entrance region over northern Iowa to provide synoptic scale forcing (**Figure 11**). Despite not having large CAPE values (less than 500 J kg^{-1}) in the early morning, the moderate amount of synoptic scale forcing was enough to develop the storms. By approximately 1500 UTC, the QS boundary was between Davenport and Chicago (**Figure 12**). The rear cold outflow combined with the southerly surface inflow appeared to "split" the system. In addition, the faster westerly mid–upper-level winds to the north of the boundary caused the eastern part of the QS boundary to turn clockwise into a north-south orientation (**Figure 13**).

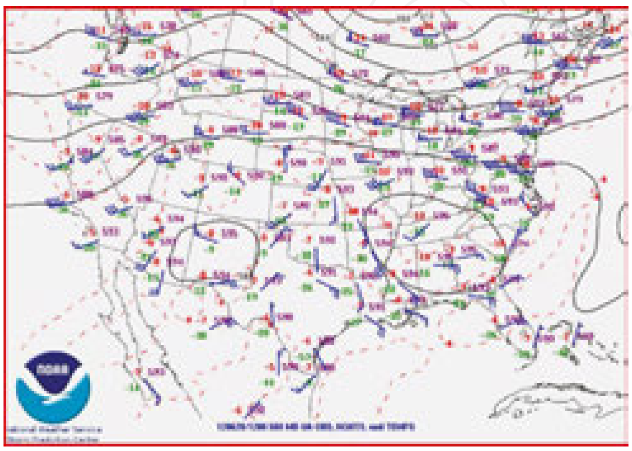

Figure 10. 500 hPa map at 1200 UTC, June 29, 2012.

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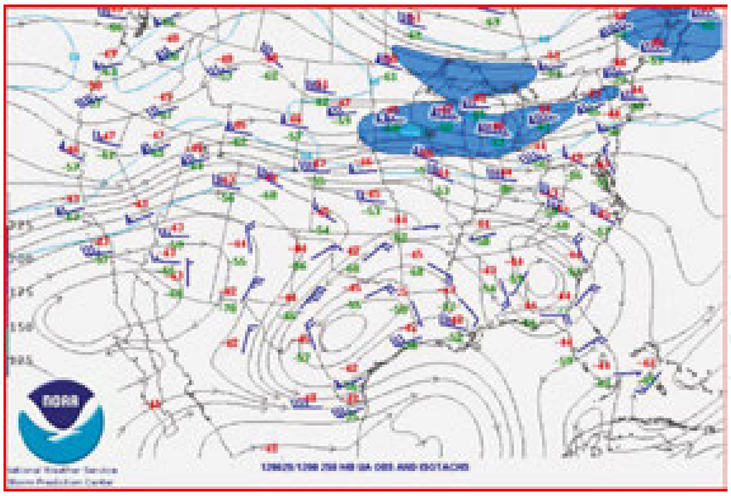

Figure 11. 250 hPa map at 1200 UTC, June 29, 2012.

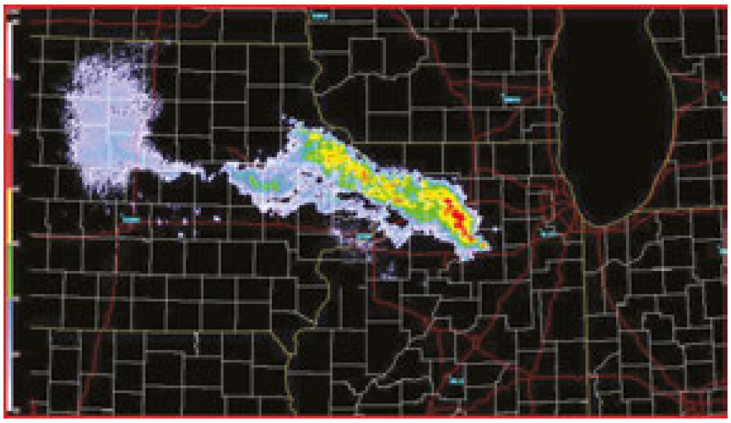

Figure 12. Base reflectivity radar at Davenport, IA at 1500 UTC, June 29, 2012.

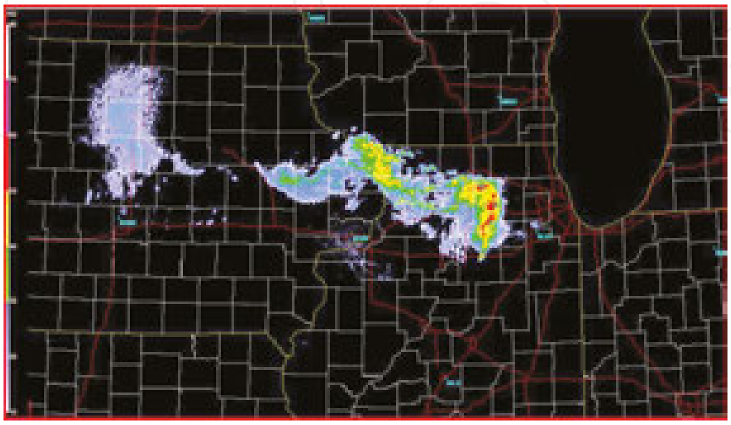

Figure 13. Base reflectivity radar at Davenport, IA at 1530 UTC, June 29, 2012.

Once the storm aligned north-south, the upper-level winds steered the system to the east. As shown in the soundings and upper-level charts, the winds were approximately 30–50 kts out of the west and exhibited very little shear. Therefore, as daytime heating occurred the convection became more of an important forcing mechanism. The daytime high temperatures approached 100°F (approximately 38°C) over much of the region with dew points near 70°F (21°C) (**Figure 14**).

Links have been made between elevated mixed layers (EMLs) and derecho formation [22]. Since EMLs exhibit very steep lapse rates in the mid-levels, they help increase the instability. **Figure 14** illustrates the steep lapse rates that existed at Charleston, WV. Combined with the extremely high surface temperatures, the air easily became unstable as the air attained the convective temperature of 36°C.

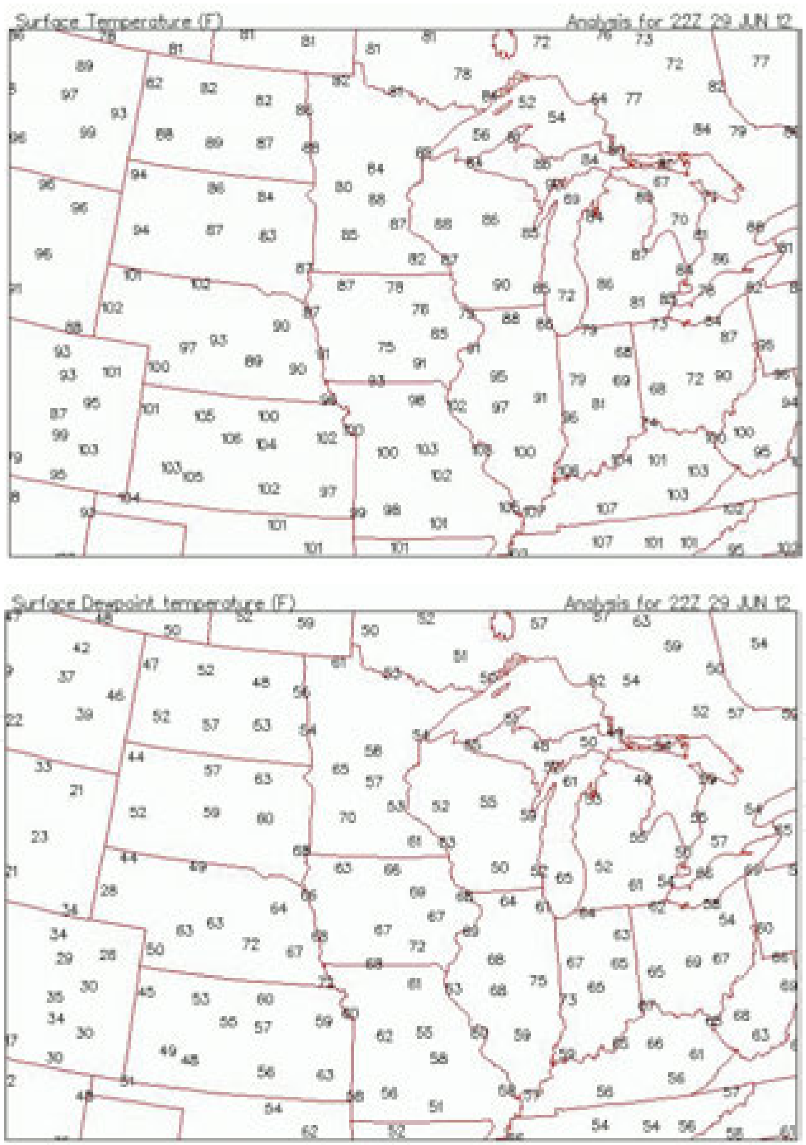

Figure 14. Surface map of temperature (a) (top) and dew point (b) (bottom) in °F for 2200 UTC, June 29, 2012.

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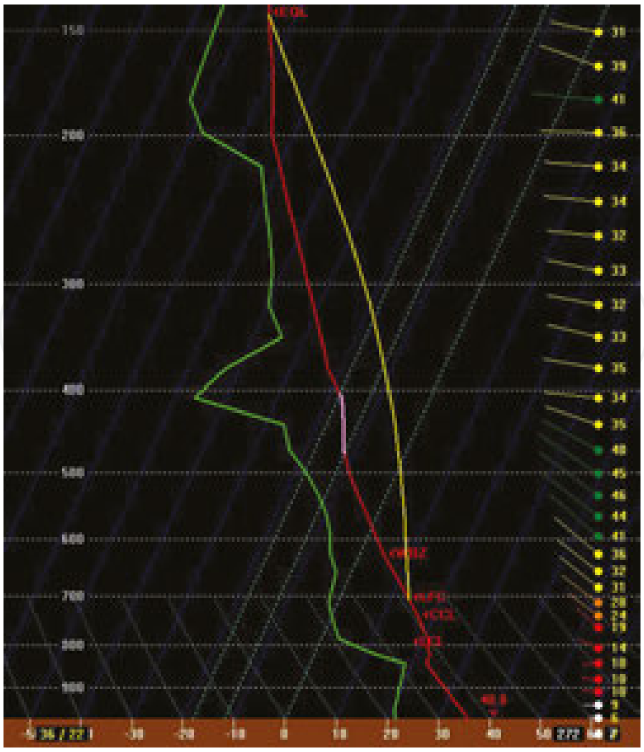

Figure 15. Sounding for Charleston, WV at 2300 UTC, June 29, 2012.

The repetitive downwind propagation continued eastward as the rapid convection ahead of the gust front created large updrafts. The rear inflow became more pronounced near Charleston, WV as the "bow" pushed farther to the east (**Figures 15** and **16a**). Behind the gust front, the cold pool became more elongated which can be seen in the base velocity image (**Figure 16b**). Volume scans show the slope of the updraft and the rear inflow jet and the formation of the cold pool (**Figure 16c**, **d**).

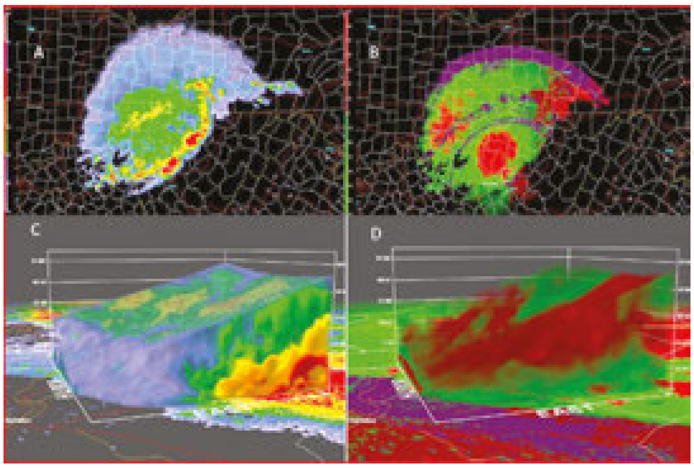

Figure 16. Charleston, WV radar at 2300 UTC, June 29, 2012; (a) base reflectivity; (b) base velocity; (c) volume scan base reflectivity; (d) volume scan base velocity.

The mean convective temperature as the derecho passed each of the six stations was 38.5°C while the mean 950 hPa to 850 hPa lapse rate was 8.61°C km^{-1} (**Table 3**). Although the mean convective temperature and lapse rates were relatively high, the standard deviation was large as the values were relatively low during the early stages but progressively increased as the derecho matured. The mean CAPE at *t (*time of derecho passage*)* was 2796 J kg^{-1} and DCAPE was 789 J kg^{-1}. Similarly the mean instability variables were relatively high but were low *during* the early stage of development. On the other hand, shear variables exhibited high values throughout the movement toward the east. Mean values for 0–3 km shear, 0–6 km shear, and 1 km storm relative inflow were 21.66 m s^{-1}, 31.5 m s^{-1}, and 9 m s^{-1}, respectively.

	t	Mean	SD	Test value
CT (°C)	1.60	38.5	2.29	37
Lapse rate (°C km^{-1})	1.31	8.61	2.17	8.5
CAPE (J kg^{-1})	0.53	2378	1740	2000
MUCAPE (J kg^{-1})	0.87	2796	1679	2200
DCAPE (J kg^{-1})	-1.42	789	363	1000
Shr (0–3) (m s^{-1})	*2.72	21.7	9.15	11.5
Shr (0–6) (m s^{-1})	*5.56	31.5	7.0	15.6
Shr (3–6) (m s^{-1})	-2.67	9.66	4.88	15
SR Inflow (m s^{-1})	*6.71	9.0	1.09	6
Helicity (m^2 s^2)	-1.69	92.5	83.39	150
PW (cm)	*11.40	4.57	0.43	2.54
BRN (unitless)	1.13	97.66	103.1	50

*Significant parameter ($p < .05$).

Table 3. One sample *t*-test for the six stations at time of derecho passage (df = 5, $p < .05$).

As a result, the one-sample t-test did not reveal that the mean ($\overline{X}$)

was larger than the test value for the convection and instability variables. However, for three shear variables (shr 0–3, shr 0–6, and Storm Relative (SR) inflow) the mean was significantly larger than the test values at the time of passage (denoted by the * next to the value of *t*). In addition, the mean precipitable water was significantly larger than the test value of 2.54 cm.

At Davenport, IA, only three variables (shr 0–3, shr 0–6, and PW) exhibited means that were significantly larger than the critical test value. **Tables 4–6** show the one-sample t-test results for Chicago, Wilmington, and Charleston in addition to the mean daily values prior to the passage of the derecho. In Chicago, the mean convective temperature was significantly larger (41.82°C) than the critical test value (37°C) as well as the shear variables and PW found in Davenport (**Tables 4**). However, farther downwind in Fort Wayne, Wilmington, Charleston, and Washington-Dulles, the mean CAPE and MUCAPE values were significantly larger than

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the respective means of 2000 and 2200 J kg^{-1}. These significant results are largely due to the extremely high CAPE/MUCAPE model values on the order of 4500–5000 J kg^{-1} found in the region.

	t	**Mean**	**SD**	**Test value**
CT (°C)	*32.95	41.82	0.33	37
Lapse Rate (°C km^{-1})	-4.12	5.46	1.62	8.5
CAPE (J kg^{-1})	-32.74	65.6	132	2000
MUCAPE (J kg^{-1})	-2.75	1620	471	2200
DCAPE (J kg^{-1})	-6.9	618	122.8	1000
Shr (0–3) (m s^{-1})	*29.53	33.2	1.64	11.5
Shr (0–6) (m s^{-1})	*33.67	38.4	1.51	15.6
Shr (3–6) (m s^{-1})	-20.00	5.2	1.09	15
SR Inflow (m s^{-1})	*8.94	10.0	1.0	6
Helicity (m^2 s^2)	-0.10	148.4	36.08	150
PW (cm)	*83.98	3.71	0.03	2.54
BRN (unitless)	-103.16	0.52	1.07	50

*Significant parameter (CT, shr 0–3, shr 0–6, SR Inflow, PW).

Table 4. One-sample *t*-test for the mean daily values prior to derecho passage at Chicago, IL (df = 4, $p < .05$).

	t	**Mean**	**SD**	**Test value**
CT (°C)	0.13	37.13	3.14	37
Lapse Rate (°C km^{-1})	-0.82	8.06	1.69	8.5
CAPE (J kg^{-1})	*3.17	3288	1284.8	2000
MUCAPE (J kg^{-1})	*19.69	3988	272.5	2200
DCAPE (J kg^{-1})	-0.43	963	275	1000
Shr (0–3) (m s^{-1})	*5.00	21.9	6.59	11.5
Shr (0–6) (m s^{-1})	*9.05	34.3	6.53	15.6
Shr (3–6) (m s^{-1})	-0.87	10.7	15.6	15
SR Inflow (m s^{-1})	*9.00	8.7	0.95	6
Helicity (m^2 s^2)	-10.2	-19.7	52.38	150
PW (cm)	*20.51	4.34	0.28	2.54
BRN (unitless)	*2.45	90.14	51.74	50

*Significant parameter (CAPE, MUCAPE, shr 0–3, shr 0–6, SR Inflow, PW, BRN).

Table 5. One-sample *t*-test for the mean daily values prior to derecho passage at Wilmington, OH (df = 9, $p < .05$).

	t	Mean	SD	Test value
CT (°C)	*6.30	41.05	2.22	37
Lapse Rate (°C km^{-1})	0.66	8.85	1.89	8.5
CAPE (J kg^{-1})	*2.36	2852.9	1253.9	2000
MUCAPE (J kg^{-1})	*6.07	3383.3	674.6	2200
DCAPE (J kg^{-1})	-0.19	985.2	269.7	1000
Shr (0–3) (m s^{-1})	*4.57	23.3	8.97	11.5
Shr (0–6) (m s^{-1})	*8.77	38.1	8.87	15.6
Shr (3–6) (m s^{-1})	-0.86	14.6	1.67	15
SR Inflow (m s^{-1})	*3.39	8.0	2.04	6
Helicity (m^2 s^2)	-10.16	-3.41	52.29	150
PW (cm)	*12.20	4.06	0.43	2.54
BRN (unitless)	1.34	79.6	76.7	50

*Significant parameter (CT, CAPE, MUCAPE, shr 0–3, shr 0–6, SR Inflow, PW).

Table 6. One-sample *t*-test for the mean daily values prior to derecho passage at Charleston, WV (df = 11, $p < .05$).

In addition to the large amount of instability, the storm relative inflow was notably high once the derecho passed Fort Wayne, IN. In Wilmington, Charleston, and Washington DC, the mean storm relative inflow was significantly larger than the critical value of 6 m s^{-1} (**Tables 5** and **6**). The mean was at least 8 m s^{-1} in both Wilmington and Charleston and often approached 12 m s^{-1} in the late afternoon from the south. Overall, the mean Downdraft CAPE was not significantly larger than the critical value because the values were low in the morning which offset the higher values in the late afternoon. However, the DCAPE values were extremely high in the late afternoon (approaching 1300 J kg^{-1}) aiding the formation of the cold pool and strengthening the derecho.

5. Conclusions

Derechos have been known to cause similar types of damage to tornadoes in terms of monetary damage and fatalities. Even though they have straight-line winds rather than rotational, the environmental conditions prior and during derecho events are comparable as well. By investigating the intense 2012 Mid-Atlantic Derecho, the importance of the key thermodynamics and dynamics could be seen.

Anomalously high wind shear in the low- and mid-levels was shown to be vital in the propagation of the storms. Low-level mean wind shear was significantly larger at the 0–3 km layer (21.7 m s^{-1}) than the critical threshold of 11.5 m s^{-1} at the time of passage at all six stations in the path. Likewise the low-mid-level mean shear in the 0–6 km level was significantly larger (31.5 m s^{-1}) than the critical threshold of 15.6 m s^{-1} at the time of passage at all six stations.

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Equally important, anomalously high heat values combined with great atmospheric instability (measured by CAPE/MUCAPE) were present at certain times during the outbreak. During the early development, CAPE/MUCAPE values were low suggesting they are not necessary as long as other synoptic forcing agents (i.e., jet streaks) are available. CAPE/MUCAPE values were not high in Illinois where the derecho formed; however, there was plenty of shear and synoptic forcing from the jet in northern Illinois to initialize the development.

Even though the synoptic uplift was absent from the lack of a jet streak in the Mid-Atlantic, surface temperatures reached the convective temperatures, triggering uplift into the unstable atmosphere. Afternoon temperatures in the area easily reached approximately 100°F (38°C). CAPE/MUCAPE model values were approximately 4500–5000 J kg^{-1} and model convective temperatures ranged between 38 and 40°C. On the other hand, the strength of the downdraft dynamics (DCAPE) was large but not found to be significantly larger.

In summary, CAPE/MUCAPE and the mean wind shear were significantly larger than their respective critical thresholds in the Mid-Atlantic. The 2012 Mid-Atlantic Derecho showed how the right combination of mean low-mid-level shear with jet stream dynamics caused it to initially develop while the intense heat led to the convective instability necessary to generate intensity. The event demonstrated that winds do not have to rotate to cause widespread damage and societal impacts and, as such, the term "derecho" was brought back to the forefront in the meteorological vocabulary.

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