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Mesoscale and Synoptic Investigation of the Tennessee March 2-3, 2020 Tornadic Supercell

Stephen Austin Powell

Mesoscale and Synoptic Investigation of The Tennessee March 2-3, 2020 Tornadic Supercell

by

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Student Name (printed)

Stephen Austin Powell________

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12-01-2023_____________

Date

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Dedication

This Capstone Project is dedicated to my parents, Stephen and Patricia Powell, and my brother, Ethan. They have provided so much support for me throughout my life and my college years at the University of Alabama in Huntsville. I would not be where I am today without their support and guidance.

I also would like to thank Dr. Lawrence Carey and Ms. Vivian Brasfield of the UAH Atmospheric Science Department for taking time out of their busy schedules to advise me on this Capstone. I am grateful to them for sharing their expertise in the field of meteorology to not only mentor me throughout this Capstone, but also on my future career and educational goals. I have been very fortunate to have been a part of an academic department that places such an emphasis on the success of its students. Finally, I would like to thank several of my classmates. John Mayhall, Ian Moeller, Connor Stoll, and Shae Deal have provided friendship and encouragement throughout the completion of this Capstone and my time at UAH.

Abstract

Supercell tornadoes form when a mesocyclone causes a rotating thunderstorm. Many of the tornadoes that occur in the United States are the result of supercells, often resulting in significant loss of life and property damage. One such supercell was found in West Tennessee on March 2, 2020 at about 10:00 PM central time. This supercell would travel across the state of Tennessee throughout the rest of the evening on March 2nd into the early morning hours of March 3rd. Over the course of its lifetime, this one supercell would produce 10 National Weather Service (NWS) confirmed tornado tracks, resulting in 25 fatalities, 309 injuries, and about $1.6 billion in damages, making it the eighth costliest tornado event in United States history. These tornadoes varied in strength, ranging from as weak as EF-0 to as strong as an EF-4 towards the end of the supercell's lifetime. While this event is now remembered as one of the most devastating tornado outbreaks in Tennessee history, it was not forecasted to be so. Neither the Storm Prediction Center (SPC) nor the National Weather Service forecasted a tornado outbreak. This research first takes a deep look at the SPC and NWS forecasts and discussions before the event in order to see what atmospheric conditions were forecasted and compare this forecast to the actual conditions. It then analyzes the observed synoptic and mesoscale conditions that allowed this tornado outbreak to unfold, incorporating radar products including reflectivity, base velocity, correlation coefficient, and spectrum width to supplement the analysis. Throughout the times analyzed, these radar products can be seen strengthening in tandem with synoptic and mesoscale condition strengthening. Ultimately, this research finds that significant warm air advection, strong upper and lower level winds, and high values of vorticity created ideal synoptic conditions for a tornado outbreak. These synoptic conditions aligned with several convenient mesoscale features to create an ideal environment for strong and destructive tornadoes.

Introduction

On March 2-3, 2020, a severe weather outbreak occurred across portions of the Southeast United States. A total of 19 National Weather Service (NWS) confirmed tornadoes impacted Southeastern Missouri, Southern Kentucky, Alabama, and Tennessee. However, the most devastating and impactful tornadoes were the result of a single supercell thunderstorm system as it moved across Tennessee. This supercell was the cause of 10 confirmed tornado tracks throughout the state (Figure 1). The storm first produced an EF-1 tornado in Gibson County, West Tennessee. It then followed an almost due easterly track parallel to Interstate 40, producing a tornado that cycled multiple times throughout its lifetime. Cycling, as it refers to tornadoes, means that the tornado that was once on the ground, lifted, then re-strengthened in the atmosphere before touching back down again as a tornado. The beginning of the track produced EF-1 damage, while further down the track EF-2 damage was surveyed throughout rural areas near the Tennessee River. The system became a substantial and devastating storm once it entered the densely populated Nashville area. The supercell strengthened, producing an EF-3 tornado, causing 2 deaths and 180 injuries, along with a little over $1 billion dollars in damage. This intensity remained as it entered the less densely-populated Mount Juliet area in Wilson County, causing 3 deaths, 50 injuries, and a little over $400 million dollars in damage (NCEI, n.d.). After producing this destruction, the tornado cycled several times before reaching its peak intensity as an EF-4 tornado which would stay on the ground for 8 miles, producing catastrophic damage. In Putnam County, Tennessee it directly caused 19 deaths, 87 injuries, and $100 million in damage (NCEI, n.d.). After this point, the track continued eastward. Cycling one more time, it finally produced an EF-0 tornado in Morgan County, East Tennessee. Along the entire path of the storm as it moved across Tennessee, a tornado was on the ground for approximately 128 miles, taking the lives of 25 individuals, injuring 309 people, and causing over $1.6 billion worth of damage along its track (NCEI, n.d.), making it the eight costliest tornado in United States history (10 Costliest U.S. Tornadoes, n.d.).

While this tornado outbreak is one for the history books, it was an overall unexpected event. In their final forecast before the event, the Storm Prediction Center (SPC) had most of the affected area under a slight risk (2/5 risk of severe weather) with Cookeville, the area that had the strongest tornado touch down, only under a marginal risk of storms (1/5 risk of severe weather) (Figure 2). Earlier forecasts had the risk even lower with the tornado risk communicated in their forecasts being little to non-existent. It is important to note that SPC convective risks not only take into account the severity of the event that is expected but also the expected areal coverage of the event (SPC Products, n.d). None of the three National Weather Service offices responsible for this area predicted this type of outcome either. Both the SPC and the NWS were predicting some severe weather across the area, but there was no indication from either organization that a supercell tornado with multiple, lengthy tracks and so much destruction was possible. This paper will take a deep look into the synoptic and mesoscale conditions that allowed this severe weather event to take place and cause as much damage as it did, despite the lower severe weather threat forecasted.

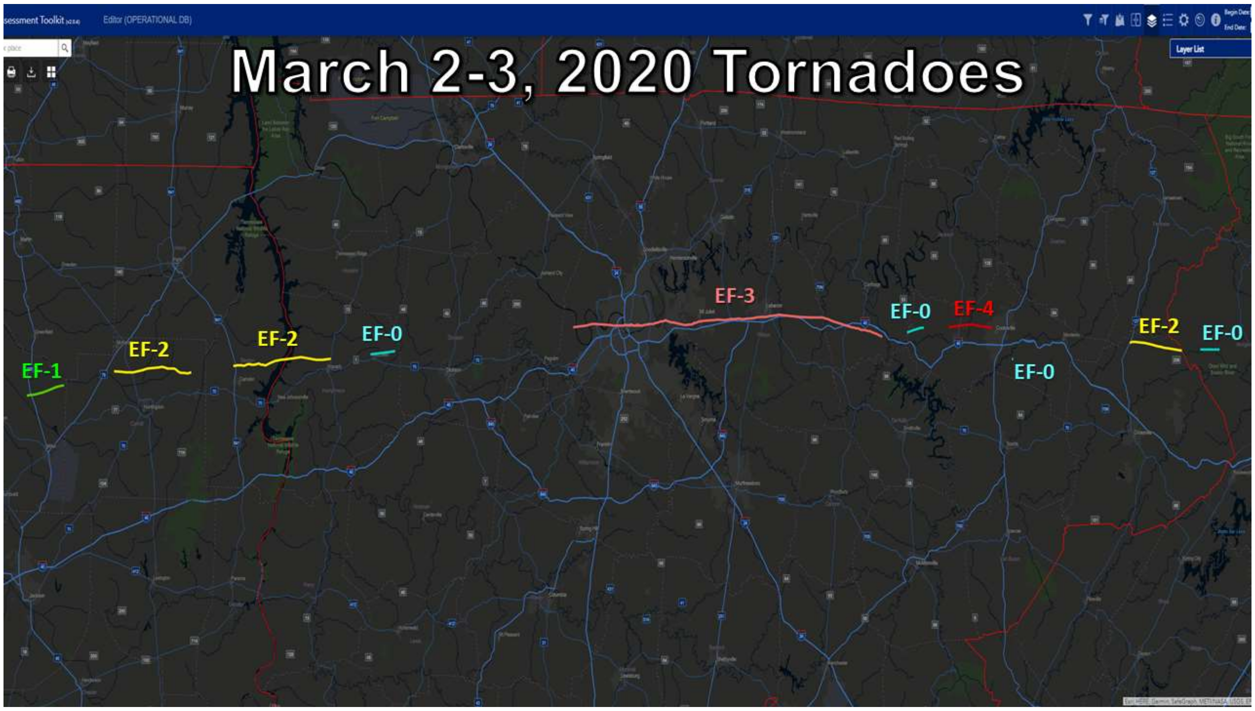

Figure 1: Tennessee Tornado Tracks from March 2-3, 2020 (NOAA Damage Assessment Toolkit).

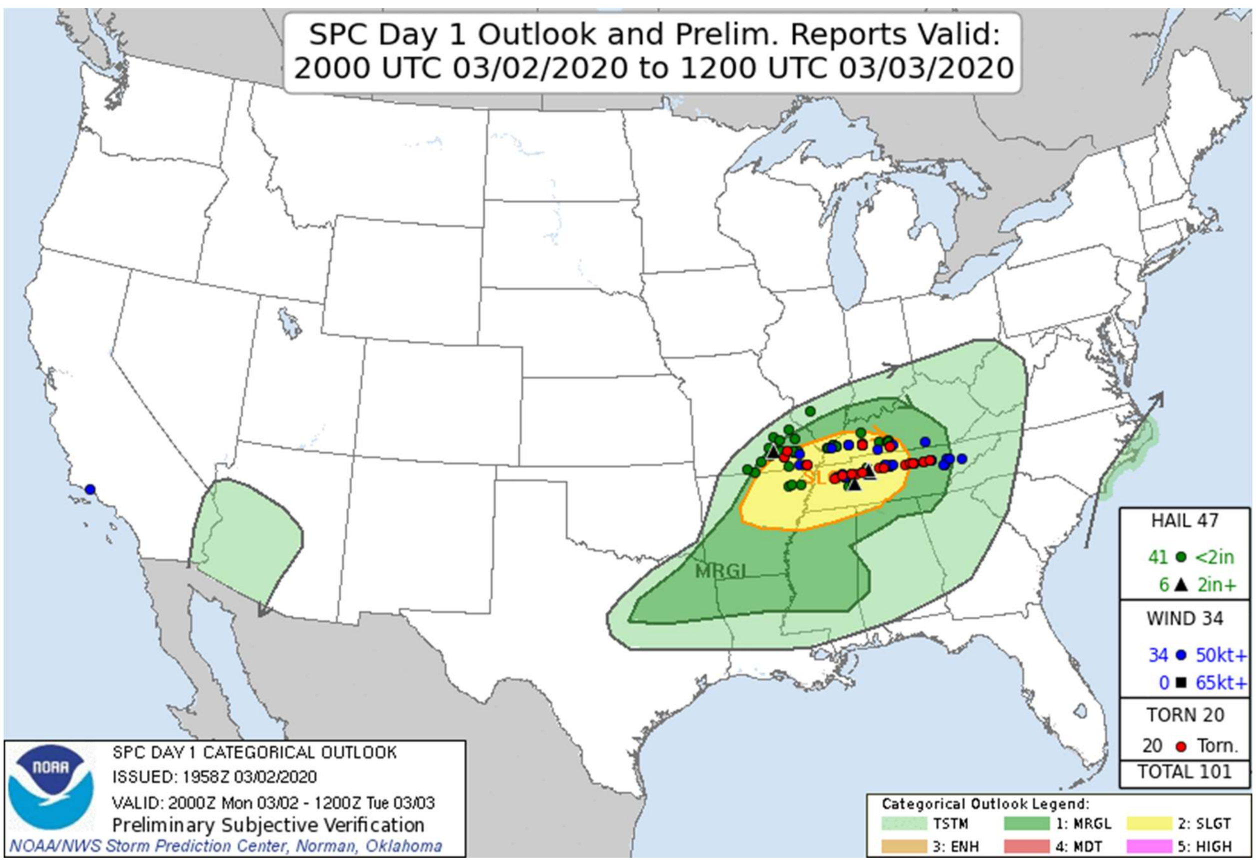

Figure 2: Final Storm Prediction Center Convective Outlook Overlayed with Storm Reports from March 2-3, 2020.

Background

For this study, multiple meteorological parameters and maps were used to evaluate the synoptic and mesoscale conditions associated with the Tennessee supercell as it made its way along the track determined by the National Weather Service Offices in Memphis, Nashville, and Morristown, Tennessee (NOAA Damage Assessment Toolkit). The tracks were rated by each of these offices based on the Enhanced Fujita (EF) scale. When discussing EF ratings throughout this research, this scale and its values are used for the basis of these ratings (McDonald et. al. 2004).

The two weather maps that are used throughout this research to analyze synoptic conditions include the 850 mb map and the 500 mb map because they both show several parameters that are useful in diagnosing severe weather potential. An 850 mb map shows conditions at about 5000 feet from the surface. These maps are commonly used to show jet streaks and any temperature advection that is occurring. A 500 mb map shows the conditions about 18,000 feet above the surface. These maps are most used to show values of vorticity, troughs, and ridge patterns. Jet streaks are defined as an area of maximum wind speeds within the jet stream, the horizontal stream of winds at high altitudes. Upper level jet steaks are important because they allow for increased lift to occur at the surface, making the associated low pressure system stronger, allowing for stronger storms to occur. Temperature advection is the change in temperature in a location due to winds either transporting colder air or warmer air. Warm air rises over cold air, resulting in increasing unstable conditions at the surface. Vorticity is the measure of the rotation of air over an area. The higher the vorticity, the more rising air there is, improving conditions for severe storms. Upper level troughs are areas of low pressure which usually result in divergence and rising air at the surface, causing unstable conditions and the development of clouds and precipitation. On the other hand, upper level ridges are areas of high pressure which usually result convergence and sinking air at the surface, resulting in calm conditions at the surface.

In addition to these synoptic-scale phenomena, mesoscale features will also be used in this analysis. A hodograph is a meteorological graph that shows the vertical wind profile at the lower levels of the atmosphere, useful for noticing rotation in the atmosphere. Vertical wind shear is the change in wind speed and/or direction with height. Typically, the greater the wind shear, the stronger a storm has the ability to become. Wind shear is often strong enough that it results in the development of supercell dynamic processes. During these dynamic processes, a rotating updraft with low pressure is located in the middle part of a storm where the strongest updraft is, resulting in stronger rotation and a more efficient dynamic process (NOAA's National Weather Service, May 2019). This process also results in the updraft of storms being tilted which leads to precipitation falling out ahead of the storm, allowing for a longer storm lifetime. The shear between 0 to 6 km is most used to assess storm potential because the wind shear at the midlevels of the troposphere are so important for the development of supercells "due to the enhanced inflow strength and the removal of precipitation from updraft" (Pilorz et. al. 2016) and also for the dynamic process mentioned above. For these reasons, the 0 to 6 km shear is what is most heavily examined in this research. The NWS classifies wind shear greater than 40 knots as being supportive of supercells (NOAA's National Weather Service, n.d.). Convective Available Potential Energy, or CAPE, is the amount of energy that is available for convection, or storm development. When CAPE is high, the atmosphere is more buoyant, allowing for air parcels to rise more easily, ultimately resulting in stronger updrafts and the increased potential for stronger storms. There are two CAPE products that are commonly examined during severe weather events, mixed layer and surface-based. Mixed layer CAPE is a measure of the instability of parcels as the rise above the surface of the Earth through the lowest 1 km of the atmosphere. Surface based CAPE is a measure of how unstable the air at the surface is, or the ability of air parcels at the surface to rise. Even if mixed layer CAPE is very high, a tornado will most likely not be able to touch down if the surface based CAPE is low, meaning that air at the surface is stable. CAPE values 1000 $\frac{J}{kg}$ or above are considered by the NWS to be sufficient for strong to severe storms to occur (NOAA's National Weather Service, 2015). Convective inhibition potential or CIN is also an important parameter to review because it is a measure of the amount of negative buoyancy in the atmosphere. The higher the CIN, the more lifting a parcel must go through before becoming unstable or buoyant, making it more difficult for severe weather to initiate. When CIN is 30 $\frac{J}{kg}$ or less, severe weather is likely, anything higher than 30 $\frac{J}{kg}$ and severe weather is not as likely to occur (NOAA's National Weather Service, 2015). Helicity is another mesoscale condition that often is used to determine how strong rotating updrafts and supercells have the ability to become. It measures the amount of vorticity that can be used by a thunderstorm, which in indicates how much rising air there is to create instability. Helicity values greater than 250 $\frac{m^2}{s^2}$ suggest an increased threat of tornadoes (NOAA's National Weather Service, 2015). A final mesoscale characteristic that is examined are lapse rates. The lapse rate is a measure of how quickly the temperature changes, or rather, cools with height. The greater the lapse rate (typically measured in $\frac{°C}{km}$), the higher the convective potential energy resulting in greater instability within the environment. Lapse rates close to 9.5 $\frac{°C}{km}$ are considered to be absolutely unstable while rates between 6 to 9 $\frac{°C}{km}$ are considered to be conditionally unstable with instability depending on the amount of moisture present in the atmosphere. (NOAA's

National Weather Service, n.d.). There are several parameters that take into account multiple mesoscale indices to assess the ability for severe storms. One of these is the significant tornado parameter. This parameter is calculated by the following equation: STP = (MLCAPE / 1500 J kg-1) * (SFC effective shear / 20 m s-1) * (effective SRH / 150 m2 s -2) * ((2000 - MLLCL) / 1500 m) * ((250 + MLCIN) / 200 J kg-1) **(**Thompson et al., 2004**)**. This equation takes into account the mixed layer CAPE, mixed layer CIN, mixed layer lifted condensation level (LCL), effective storm relative helicity, and the effective bulk wind difference over the lower half of the storm to predict the possibility of EF-2 to EF-5 tornadoes developing in an environment **(**Thompson et al., 2004**).** These parameters and indices will be examined for this case study to assess the severe weather potential for this event and how the it evolved.

Radar imagery is used throughout this research to analyze the strength of the storm at different points throughout the track. Several radar products are used, including base reflectivity, base velocity, correlation coefficient, and spectrum width. Base Reflectivity is the measure of the amount of energy that is returned to the radar from a given radar scan. It is measured in dBZ, or decibels of energy. Higher values of Base Reflectivity values generally point towards stronger or strengthening storms, heavier rainfall, and in some cases could mean larger debris is present in the atmosphere. Base Velocity is the measure of winds moving towards and away from the radar. Positive values are winds going away from the radar while negative values are winds going towards the radar. For the radar imagery included in this research, green colors on the radar are winds moving towards the radar while red colors are winds moving away from the radar. The brighter these colors, the stronger the wind speeds. When these two colors are seen meeting on the radar, this is known as a velocity couplet, a strong indication that rotation could be ongoing in the area. Correlation Coefficient is a measure of how similar the objects that are detected by the radar are to each other in shape and orientation. The closer these values are to 1 indicates that the radar is picking up on objects with similar properties. The lower these values, the wider the range of properties between items in the atmosphere, indicating that debris is likely in the atmosphere, pointing towards a likely tornado. Past research has concluded that when Base Reflectivity values are greater than 30 dBZ and Correlation Coefficient values are less than 0.7 in an area that corresponds with a rotation signature on radar reflectivity is indicative that debris is being lofted into the atmosphere (Schultz et al., 2012). Spectrum Width is a measure of the variation of velocity that is observed within a storm. Higher values indicate that turbulence is likely ongoing, pointing to the possibility of rotation and a tornado.

Hypothesis & Research Questions

Due to the devastation that resulted from this supercell, and the surprise that it was to forecasters at the SPC and NWS, the main goal of this study is to determine what synoptic and/or mesoscale conditions came together to allow for this supercell to develop and intensify in areas where no form of severe weather was expected, especially a strong tornado. My hypothesis is that there are several synoptic and mesoscale conditions that drastically changed from the forecast, allowing for this powerful supercell. This research will analyze these conditions and also look at specific points in the track where the strength of the supercell either became stronger or much weaker.

Data & Research Methods

The radar data used for this investigation was obtained from the NOAA National Centers for Environmental Information website (NCDC, n.d.). This site provided the Nexrad Level II Base Data from the KNQA, Memphis, Tennessee Radar on March 3 from 4:00 UTC (10 PM on

March 2, 2020) to 6:00 UTC (12 AM on March 3, 2020) and the same data from KOHX, Nashville, Tennessee Radar on March 3, 2020, from 6:00 UTC (12 AM on March 3, 2020) to 9:00 UTC (3 AM on March 3, 2020). This time period includes the radar images from just before the supercell spawned a tornado in Gibson County, as it made its way through Nashville, Mount Juliet, and Cookeville, and finally when it lifted in Morgan County. GR2Analyst was used to read the Nexrad Level II data. For several key points of interest mentioned in the storm survey during the track, the Base Reflectivity (BR), Base Velocity (BV), Correlation Coefficient (CC), and Spectrum Width (SW) were used to analyze the storm mode and track.

Mesoscale and Synoptic Conditions were obtained from the Storm Prediction Mesoanalysis Archive Page (SPC Mesoanalysis Archive Page), this allowed for data analysis of multiple mesoscale and synoptic parameters that are commonly associated with tornadoes. The data used to create these maps from 04Z, 06Z, and 08Z on March 3, 2020 which show moisture advection, temperature advection, jet streaks (knots), vorticity advection, surface to 6 km shear (knots), effective bulk shear (knots), 0-1 km and 0-3 km storm relative helicity ($\frac{m^2}{s^2}$), mixed layer and surface based CAPE ($\frac{J}{kg}$) & CIN ($\frac{J}{kg}$), the significant tornado parameter, and lapse rates ($\frac{°C}{km}$) came from the Rapid Refresh (RAP) model (Storm Prediction Center, 2001). These maps were created at the top of each hour using RAP model guidance that was vetted using a sounding analysis routine. For these parameters, it was analyzed as to whether the impressive values of each parameter were in the area of the supercell, causing it to strengthen and overperform forecasts.

Analysis

Before beginning analysis, it is important to note for the National Weather Service Analysis, discussions from NWS Nashville were analyzed. As noted above, this event crossed over into three NWS County Warning Areas (CWAs) (Memphis, Nashville, and Morristown), but since the Nashville CWA was most heavily affected, its Area Forecast Discussions (AFDs) were used for this analysis. Additionally, 04Z, 06Z, and 08Z on March 3, 2020 were the times chosen to examine maps showing the above mesoscale and synoptic conditions due to 04Z being the time the supercell first developed in West Tennessee, 06Z being close to the time it strengthened as it moved through Nashville, Tennessee, and 08Z being around the time that it became its strongest along the whole track in Cookeville, Tennessee and subsequently weakened not long after.

a) Storm Prediction Center/National Weather Service Pre-Event Analysis

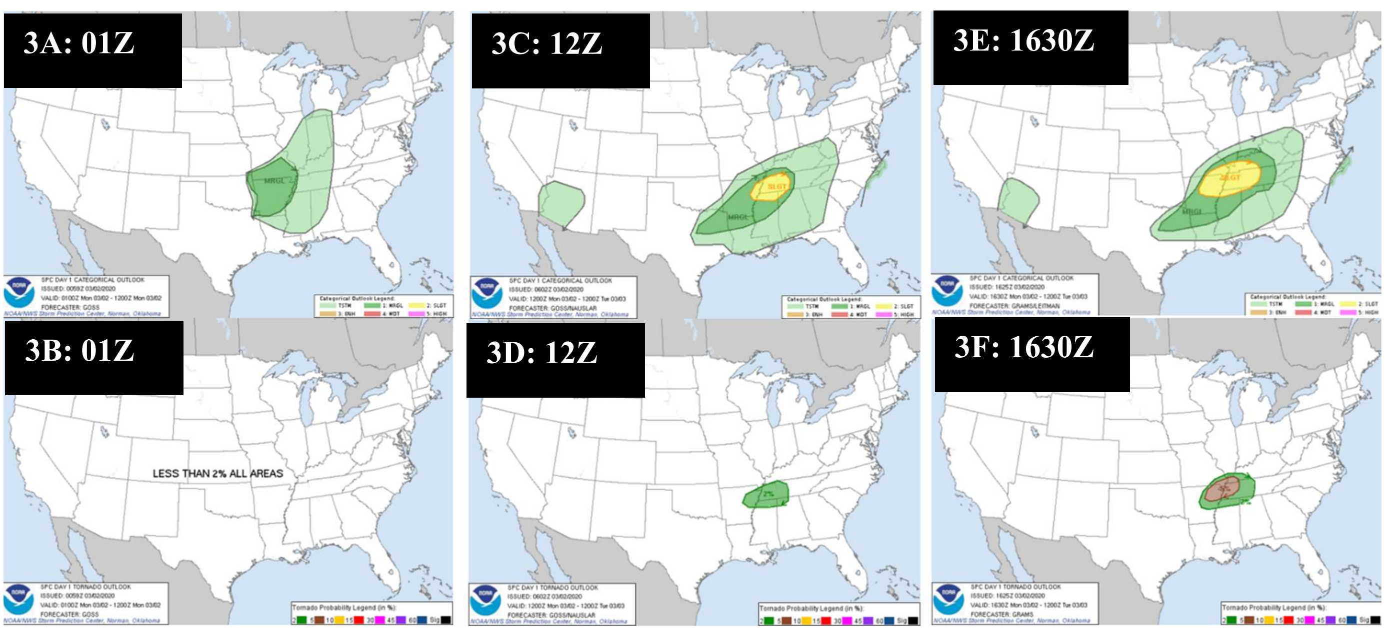

Figure 3: March 2, 2020 Storm Prediction Center Convective Outlooks (Top Row) & Tornado Outlooks (Bottom Row)
3A: Convective Outlook Issued at 01Z; **3B:** Tornado Outlook Issued at 01Z;
3C: Convective Outlook Issued at 12Z; **3D:** Tornado Outlook Issued at 12Z;
3E: Convective Outlook Issued at 1630Z; **3F:** Tornado Outlook Issued at 1630Z

Row	Time/Date Issued	Convective Outlook	Advection	CAPE	Lapse Rates	Jet Streaks	Instability	Shear	Other Notable Comments	Expected Threats
1	1Z March 2, 2020	General Thunderstorms	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2	12 Z March 2, 2020	Slight for Nashville Westward; General Thunderstorms for Lebanon Eastward	Warm Air Advection	N/A	N/A	N/A	N/A	"Favorable"	Cold Front Moving Through Area with convection ahead of it. Expected time: 23 to 4Z.	"Primary risk appears to be hail, but locally damaging winds and even a couple of tornadoes."
3	13 Z March 2, 2020	Slight for Nashville Westward; General Thunderstorms for Lebanon Eastward	N/A	1500 J/kg	Greater than 8 C/km	N/A	N/A	Effective Bulk Shear Near 40 knots; Low level could increase	Low level moistening ahead of front.	Large hail and low-end tornado threat dependent on shear.
4	1630Z March 2, 2020	Slight for Lebanon Westward; Marginal For Cookeville Eastward	N/A	1000 to 1500 J/kg	Greater than 8 C/km	N/A	N/A	Bulk near 40 knots; Increasing low-level shear	Timing most likely between 03-07Z	"Large hail, a couple of tornadoes, and damaging winds."
5	20Z March 2, 2020	Slight Risk For Lebanon Westward. Marginal Risk Eastward.	N/A	1000-1500 J/kg	Greater than 8 C/Km	N/A	N/A	Effective bulk shear close to 40 knots, low-level shear expected to increase through the evening	Boundary layer stabilization expected to overcome any conditions causing instability, decreasing severe threat.	"Very large hail and a couple of tornadoes"

Table 1: Notable Synoptic and Mesoscale Parameters mentioned in SPC Outlooks.

Row	Time/Date AFD Issued	Advection	CAPE	Lapse Rates	Jet Streaks	Instability	Shear	Other Notable Comments	Expected Threats
1	1Z March 2, 2020	Warm Advection From Being in Warm Sector of Frontal System	N/A	N/A	"Strengthening"	Weak	"Good"	N/A	Large Hail and Strong Wind
2	12Z March 2, 2020	N/A	N/A	Steepening near 7.5 to 8 C/km	N/A	"Good"	"Good"	Dry Air Aloft. "Low-end severe weather threat."	Wind & Tornadoes
3	1630Z March 2, 2020	N/A	Higher than 500 J/kg	Steep	N/A	Increasing throughout afternoon	Strong deep layer	N/A	Large Hail, Damaging Winds, Isolated Tornadoes
4	20Z March 2, 2020	N/A	Remain Elevated	Steep	N/A	Increasing throughout afternoon	Deep Layer Strong, low level increased since previous discussion	Low level helicity trending up with new model runs	"Decent Hail Threat and Possible Tornadoes"
5	4Z March 3, 2020	N/A	Around 500 J/kg	N/A	N/A	Will decrease after sunset due to loss of daytime heating.	Bulk shear greater than 60 knots	N/A	"Damaging winds and hail continue to be the main concern, though an isolated tornado cannot be ruled out."

Table 2: Notable Synoptic and Mesoscale Parameters mentioned in NWS Area Forecast Discussions (AFDs)

<u>March 2, 2020 1Z (7 PM on March 1)</u>

SPC Analysis (Table 1 Row 1): In the first convective outlook issued on the day of the event, the path of destruction that would result from the supercell tornado was in a “General Thunderstorm Outlook.” (Figure 3A). This outlook is summarized by the SPC as “no severe thunderstorms expected” (SPC Products, n.d). In the outlook discussion, the forecaster mentioned some synoptic conditions that could lead to some severe weather in Missouri and Arkansas but none in Tennessee. Tornadoes were not mentioned at this time as there was no tornado outlook for any location in the country (Figure 3B).

NWS Analysis (Table 2 Row 1): This discussion mentioned several synoptic and mesoscale conditions that could allow for the possibility of large hail and strong winds, but tornadoes were not mentioned as a possible threat.

<u>March 2, 2020 12Z (6 AM)</u>

SPC Analysis (Table 1 Row 2): The outlook issued at this time forecasted a greater severe weather threat for part of Tennessee. This outlook had areas from Nashville Westward in a level 2/5 “Slight Risk” (Figure 3C). This risk is defined as “isolated to scattered severe storms expected” (SPC Products, n.d). A point of interest, Cookeville, where the strongest tornado along the whole path, an EF-4, touched down was still in a general thunderstorm risk at this point, while Nashville was on the edge of the slight risk. The discussion mentions several favorable synoptic conditions for severe storm development, but the forecaster points out that capping, warm air aloft prohibiting the development of thunderstorms, was expected to limit the development of severe storms, the main reasoning for only a slight risk of storms. A 2% chance of tornadoes was assigned to Western portions of Tennessee with this outlook (Figure 3D).

NWS Analysis (Table 2 Row 2): The office issued a new forecast discussion at 2:33 AM, and this was the discussion that was issued closest to the 12Z SPC outlook discussion. In this discussion, the forecaster mentioned how severe weather looks more likely. The focus was quickly changing from a heavy rain event to a "low-end severe weather threat." The forecaster writes "I wouldn't be surprised to hear the evening shift talk about rotating storms."

March 2, 2020 13Z (8 AM)

SPC Analysis (Table 1 Row 3): In this convective outlook, the categorical outlook map and probabilistic tornado graphic stayed identical to the 12Z, but this discussion gave more weight to the possibility of severe storms that evening.

March 2, 2020 1630Z (8:30 AM)

SPC Analysis (Table 1 Row 4): At this point, the SPC seemed to gain more confidence that some tornadoes were likely, extending the marginal and slight risks further eastward (Figure 3E) and upping the tornado threat to 5% across portions of West Tennessee (Figure 3F). Mesoscale and synoptic conditions also seem to be favorable for severe storm development. Of interest, at this point, the forecasters seem to nail down the timing as in the discussion it was noted that 03 to 07Z seems to be the most likely time frame for storms to develop. These times are almost exactly when the tornado outbreak occurred across Tennessee. 04Z is the time when the first tornado touched down in West Tennessee and 08Z is when the tornado was at its peak strength in Cookeville, Tennessee. In this outlook, Cookeville was included in the marginal level 1/5 risk.

NWS Analysis (Table 2 Row 3): In the discussion written at 10:54 AM, the NWS mentions that models continue to show instability increasing across the area throughout the afternoon. However, the emphasis at this point is still on large hail and damaging winds.

<u>March 2, 2020 20Z (2:00 PM)</u>

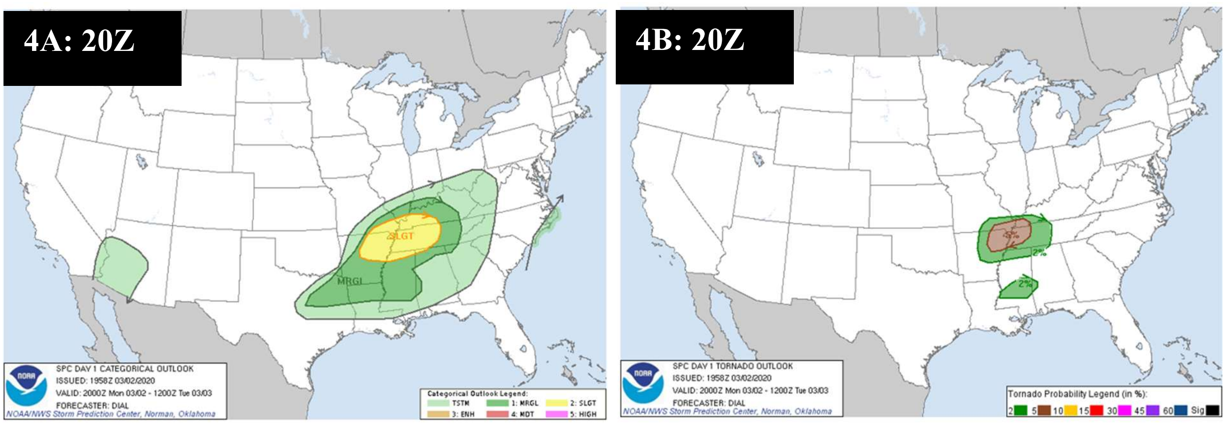

Figure 4: Final Storm Prediction Center Convective Outlook (Left) & Tornado Outlook (Right) Issued Before Event
4A: Convective Outlook Issued March 2, 2020 at 20Z; **4B:** Tornado Outlook Issued March 2, 2020 at 20Z;

SPC Analysis (Table 1 Row 5): The final convective outlook to be issued before the event was 20Z (2PM). This outlook once again spread the marginal risk a little further to the east, but the slight risk was left alone (Figure 4A). Also, the probabilistic tornado graphic as it affected Tennessee was left the same (Figure 4B). The forecaster noted the reasoning for not upgrading the risk was due to the expectation that the storms would be initiated after sunset, which they were, and the boundary layer stabilization would be enough to overcome the conditions that created the instability in the atmosphere. All of this to say, when the sun goes down and the atmosphere loses that source of heating, generally storms are not as prone to become severe due to the lack of heat. Other than this input, the discussion was mostly the same as the 1630Z.

NWS Analysis (Table 2 Row 4): In the AFD written at 2:35 PM, the forecaster states that instability is forecasted to increase across the area as the afternoon progresses and he "can not rule out a tornado or two tonight." It is clear between this and the previous discussion that the necessary severe weather parameters are strengthening, and the office is becoming more concerned about the possibility of tornadoes.

Note: While the last SPC Convective Outlook was issued at 2:00 PM, the National Weather Service wrote one more area forecast discussion while the event was ongoing. The analysis within this discussion is included below to provide more background to what forecasters were seeing while the event was ongoing.

March 3, 2020 04Z (10:00 PM)

NWS Analysis (Table 2 Row 5): In the AFD issued at 10:14 PM, the forecaster believes that instability will decrease further into the evening due to the lack of daytime heating. It is noted that the storms could stay severe and organized depending upon how the low and mid-level wind fields act. The severe weather threat is still limited to "Damaging winds and hail continue to be the main concern, though an isolated tornado cannot be ruled out." Even 1 hour before the event starts in West Tennessee, forecasters at NWS Nashville are still not publicly indicating the possibility of a large-scale tornado outbreak like what was observed.

Now that this paper has reviewed the convective outlooks from the SPC and area forecast discussions from NWS Nashville, it will now analyze the actual synoptic and mesoscale conditions that were present that allowed this event to exceed expectations and cause as many destructive tornadoes as it did.

b) Synoptic Analysis

Before beginning the analysis of the synoptic conditions, it is important to note the general setup that allowed this event to unfold. These storms were ultimately located in the warm sector out ahead of the midlatitude cyclone and associated cold front. There was a cold front behind these storms, but the forcing was from a warm front that was located out ahead of the low pressure system and cold front as seen from Figure 5 showing the Weather Prediction Center's National Forecast Chart.

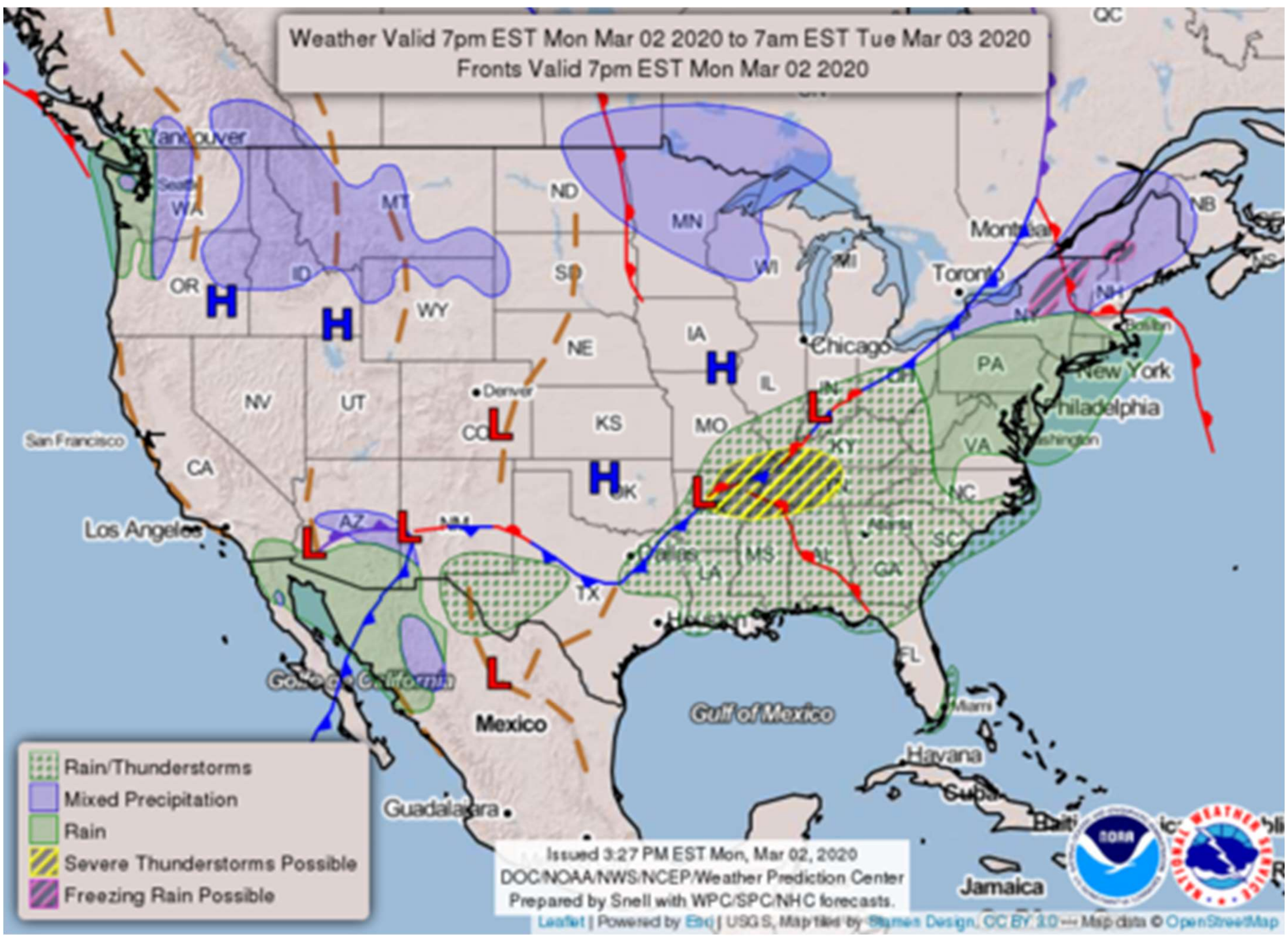

Figure 5: Weather Prediction Center's National Forecast Chart Issued at 2:27 CST on March 2, 2020.

<u>04Z (10 PM March 2nd)</u>

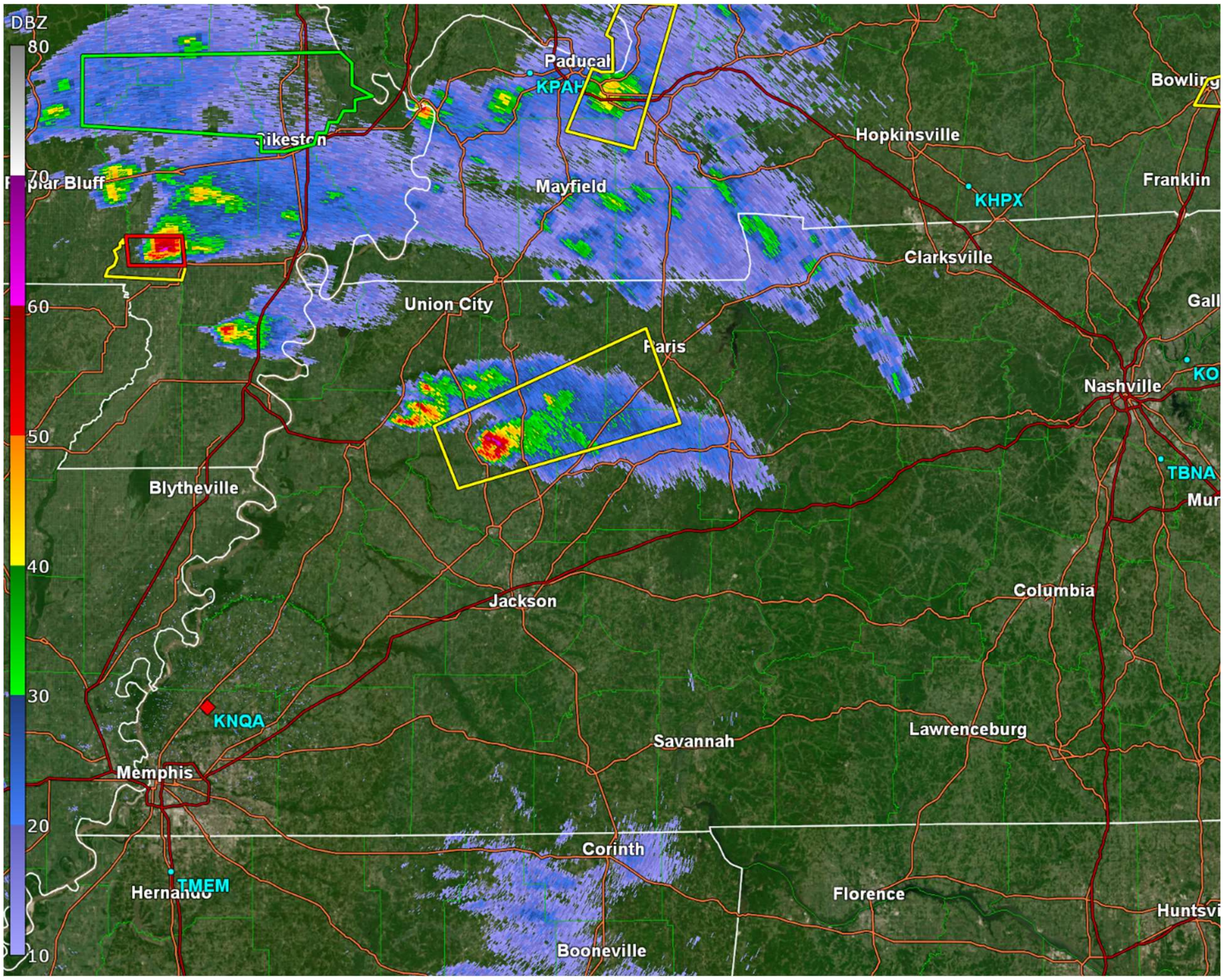

Figure 6: KNQA, Memphis, TN, Base Reflectivity (dBZ) Radar Image of Developing Storms at 0403Z on March 3, 2020

At 10 PM, the storms were beginning to develop in West Tennessee (Figure 6). At the time of the radar imagery, a severe thunderstorm warning had already been issued for a cell in West Tennessee. However, no convective watches, severe thunderstorm or tornado, were in effect for West Tennessee at this time. At 10:12, this cell would produce an EF-1 tornado, the first of many resulting from this dangerous supercell. Just before the development of this tornado, several synoptic conditions were showing favorable conditions for tornadic development, as discussed below.

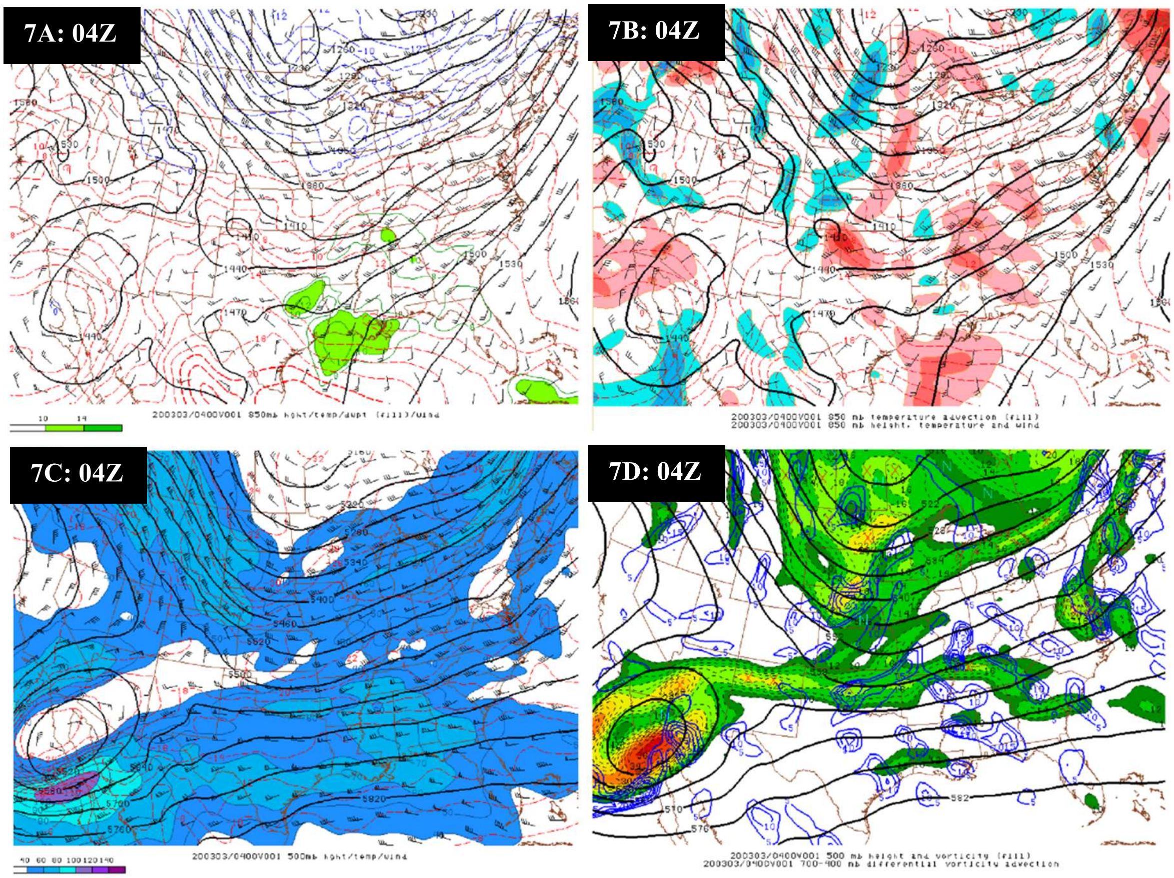

Figure 7: 4Z Synoptic Maps (SPC Mesoanalysis Archive) **7A:**850 mb Chart Showing Moisture Advection; **7B:** 850 mb Chart Showing Temperature Advection Map; **7C:**500 mb Chart Showing Jet Streaks (Knots); **7D:** 700-400 mb chart Showing Vorticity Advection

The 850 mb chart shows a negatively tilted trough forming from a center of low pressure centered near Wisconsin into Canada (Figure 7A). This trough stretches all the way to West Tennessee and indicates areas of lower pressure. To the east of the trough is upper level divergence, leading to convergence and rising air at the surface. This rising air creates convective instability in this area, resulting in the formation of some stronger storms. Additionally, this chart indicates stronger warm air advection (WAA) ongoing at the lower levels in West Tennessee (Figure 7B), bringing warm surface temperatures to the area to fuel the storms. The 500 mb chart shows very strong winds at the upper levels, with jet streaks between 60 and 80 knots (Figure

7C), and decent vorticity advection values near 16 knots (Figure 7D). All of these synoptic features point towards a decent environment for severe storm development.

06Z (12 AM March 3rd)

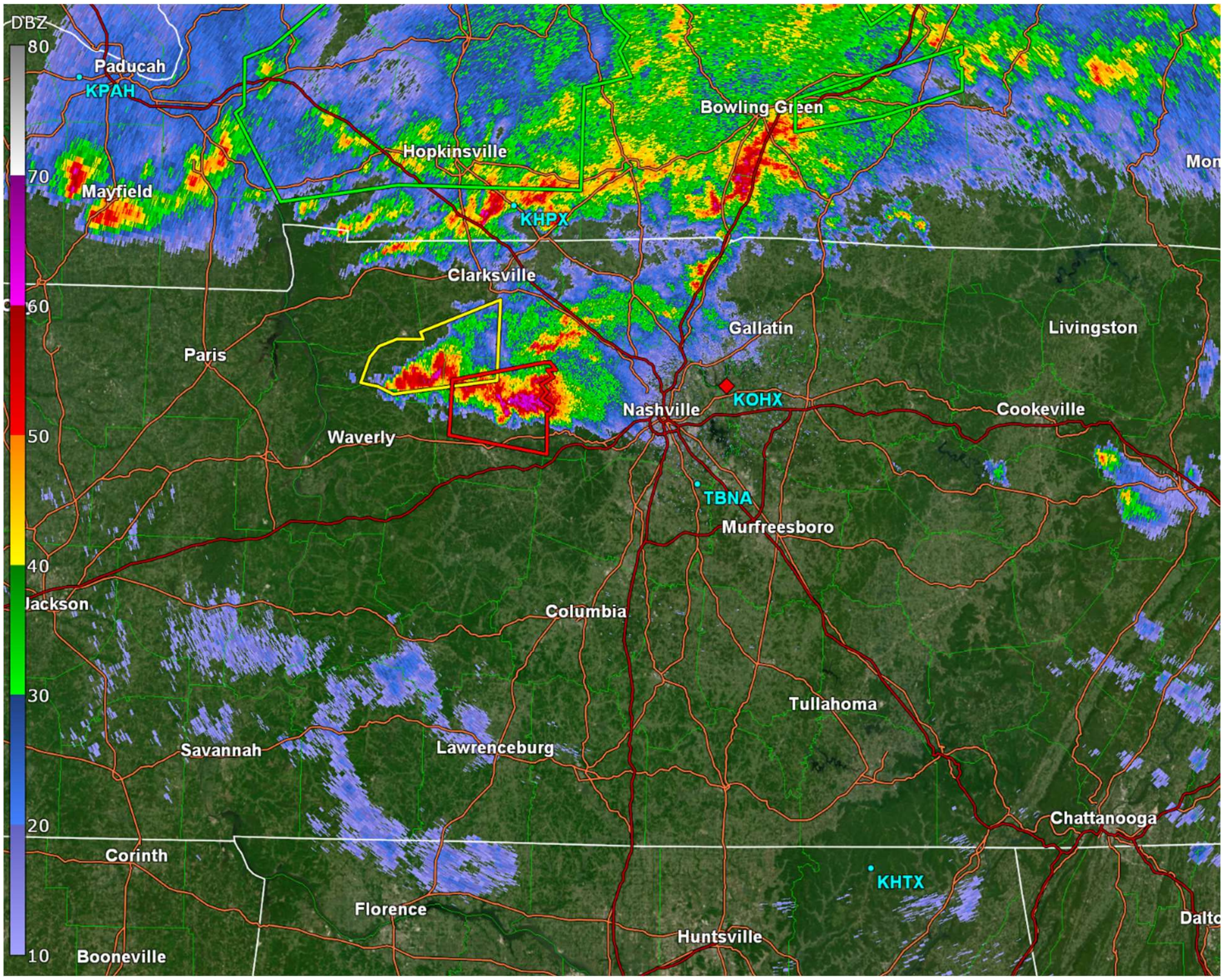

Figure 8: KOHX, Nashville, TN, Base Reflectivity (dBZ) Radar Image of Supercell West of Nashville at 0605Z on March 3, 2020.

At 12 AM, a tornado warning was in effect for several counties west of Nashville. A tornado watch had been issued for most of Middle Tennessee about 40 minutes earlier, but this tornado warned storm had already produced two EF-2 tornadoes in West Tennessee and one EF-1 tornado at this point. However, the affected areas were mostly rural, so the severity of this event was not well documented at this time. The storm showed no sign of weakening as it approached Nashville and radar imagery continued to point towards a possible tornado as seen from the hook shape in located in the red tornado warning box (Figure 8).

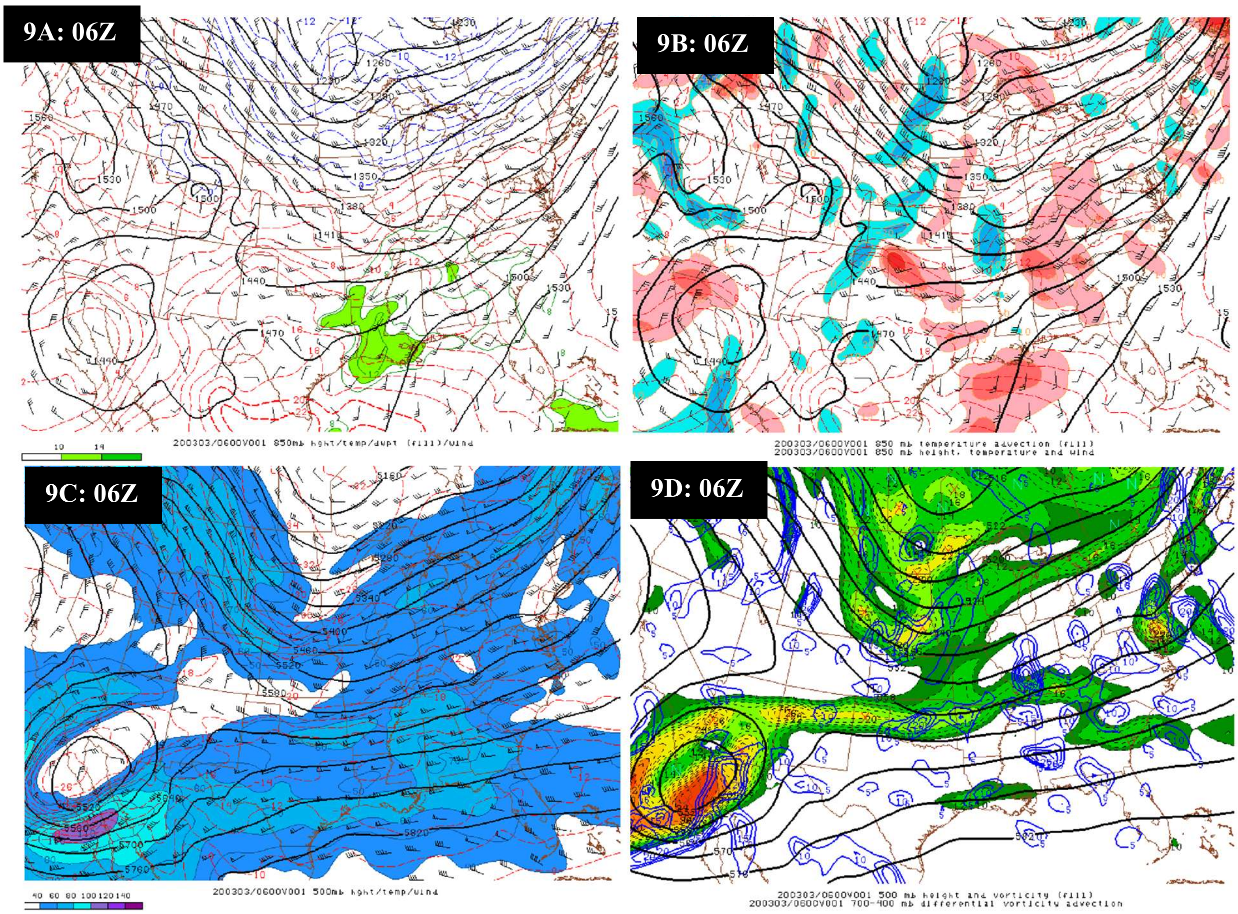

Figure 9: 06Z Synoptic Maps (SPC Mesoanalysis Archive) **9A:**850 mb Chart Showing Moisture Advection; **9B:** 850 mb Chart Showing Temperature Advection Map; **9C:**500 mb Chart Showing Jet Streaks (Knots); **9D:** 700-400 mb chart Showing Vorticity Advection

The 850 mb map shows the trough continuing to move farther to the east, now stretching into Middle Tennessee (Figure 9A). It has also become more negatively tilted since 04Z, indicating that the system has intensified in the last 2 hours. The warm air advection has also become more pronounced in the area of the supercell (Figure 9B), providing for warmer air to fuel severe storms. These features line up with a strong upper-level jet close to 80 knots (Figure 9C) and vorticity advection still near 12 knots (Figure 9D). Compared to the maps at 04Z, these synoptic features are more supportive for the continued strengthening of what are already severe storms.

08Z (2AM March 3rd)

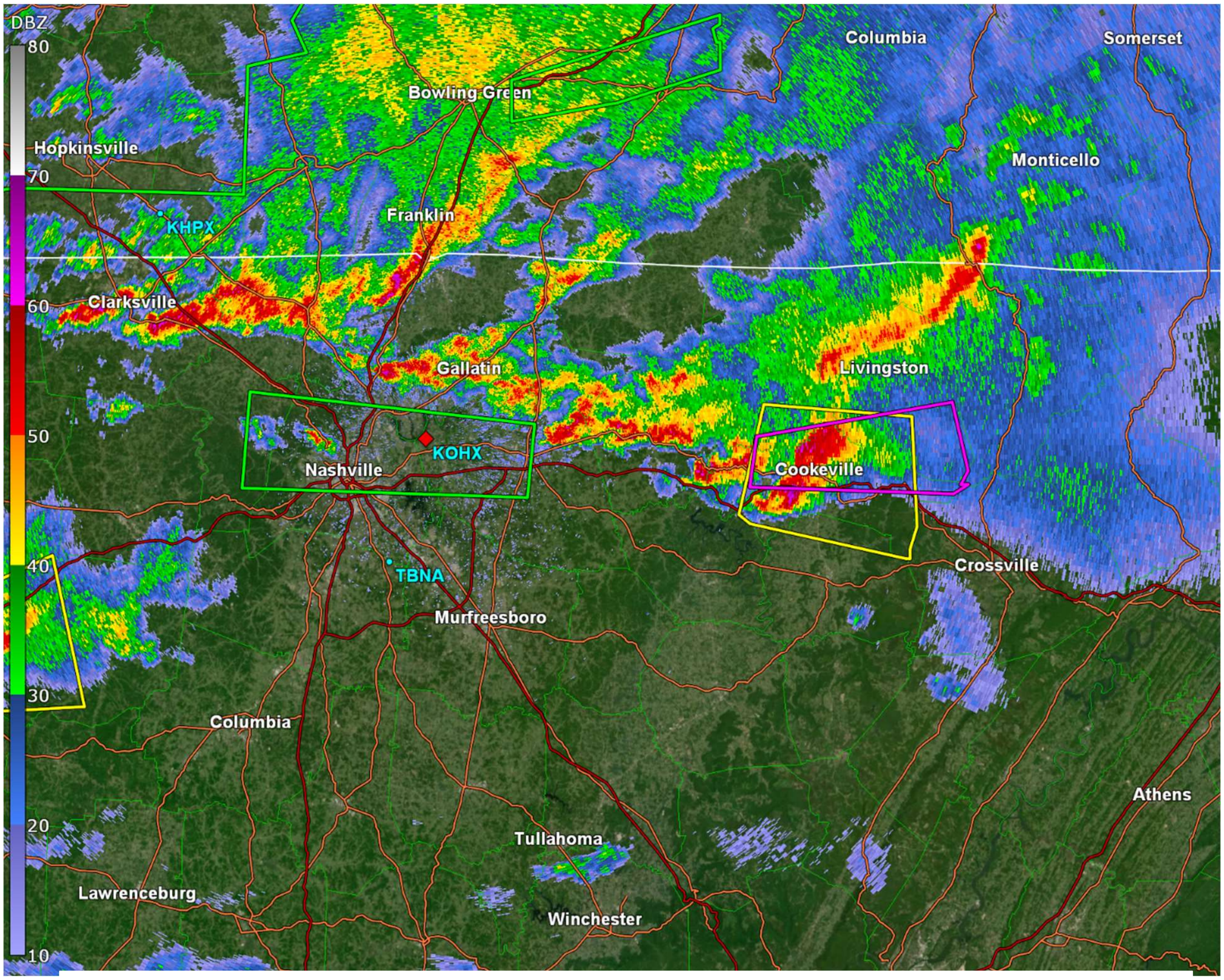

Figure 10: KOHX, Nashville, TN, Base Reflectivity (dBZ) Radar Image of Storm During its Strongest Track as it Moves Through Cookeville at 0753Z on March 3, 2020.

By 2 AM CST, the storm had left a path of destruction through Metro Nashville and several surrounding suburbs. The severity of this event was well known by the damage documented in well populated areas and video captured by news stations in Nashville as it moved through Downtown. At this point, the storm had produced two EF-0 Tornadoes, one EF-1, two EF-2, and one EF-3 tornado, but the strongest tornado was about to be produced, an EF-4 just west of Cookeville (Figure 10).

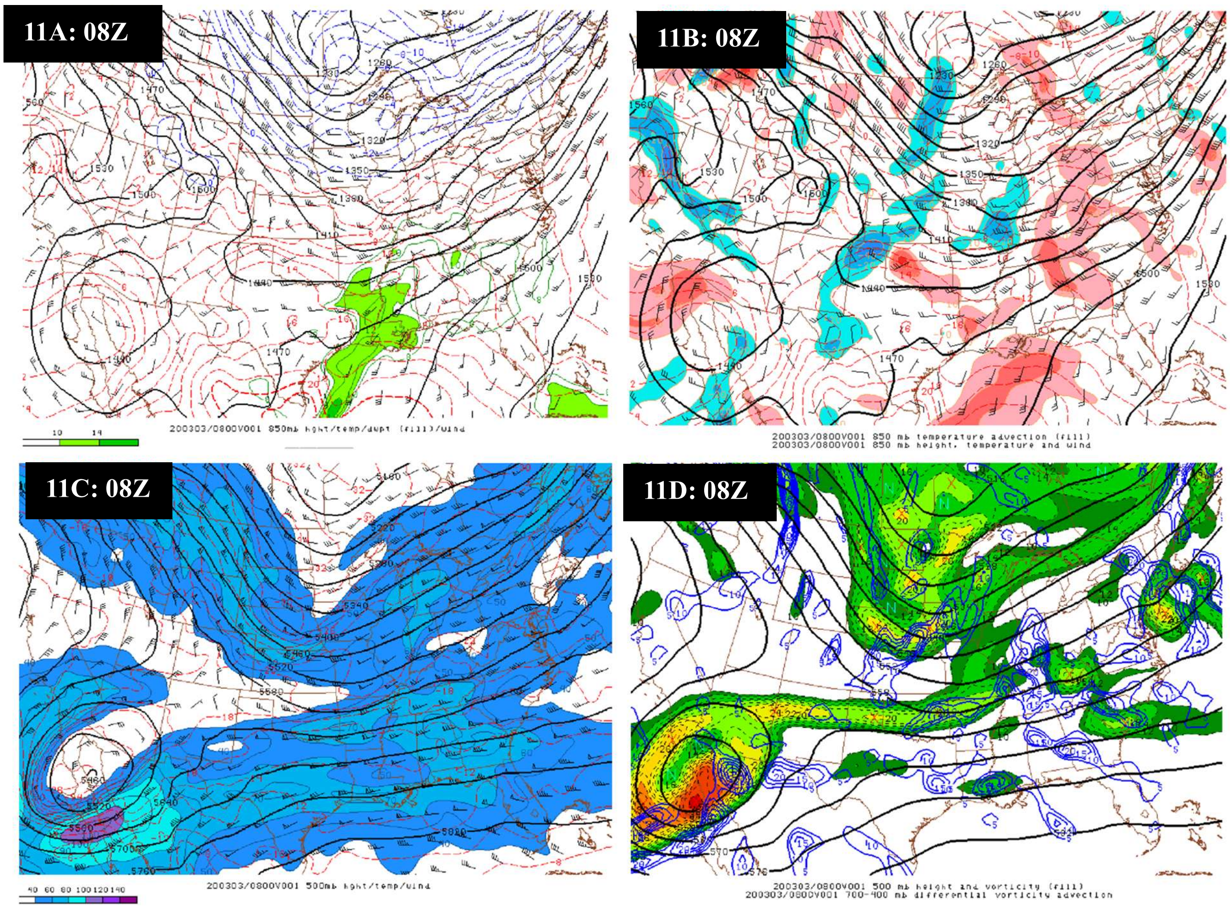

Figure 11: 08Z Synoptic Maps (SPC Mesoanalysis Archive)
11A: 850 mb Chart Showing Moisture Advection; **11B:** 850 mb Chart Showing Temperature Advection Map; **11C:**500 mb Chart Showing Jet Streaks (Knots); **11D:** 700-400 mb chart Showing Vorticity Advection

As with the 06Z maps, the synoptic conditions continued to show improved conditions for the development of severe storms. The 850 mb map shows the deepening negative trough dipping down across Eastern sections of Middle Tennessee (Figure 11A). Substantial warm air advection (Figure 11B) along with upper-level winds still reaching near 65 knots (Figure 11C) are in the area of the supercell. Finally, vorticity advection values are near 15 knots (Figure 11D), which are the strongest values seen in the area of the supercell for all time periods. The synoptic conditions once again point towards improving atmospheric conditions for the continued strengthening of already severe thunderstorms.

c) Mesoscale Analysis

To set the scene for the mesoscale analysis, it is first important to look at the observed sounding conditions found earlier in the day. The latest sounding data in Nashville before the event was collected on March 3, 2020 at 00Z (6 PM on March 2nd) (Figure 12). Looking at the sounding shows that there is some wind shear at the surface, close to 10 knots, and CAPE values are close to 400 $\frac{J}{kg}$. These values are not very impressive and would not indicate a severe weather outbreak was possible, especially one anywhere near the magnitude of what occurred. For the rest of this paper's mesoscale analysis, several important mesoscale conditions, including the CAPE, will be analyzed as the event progressed.

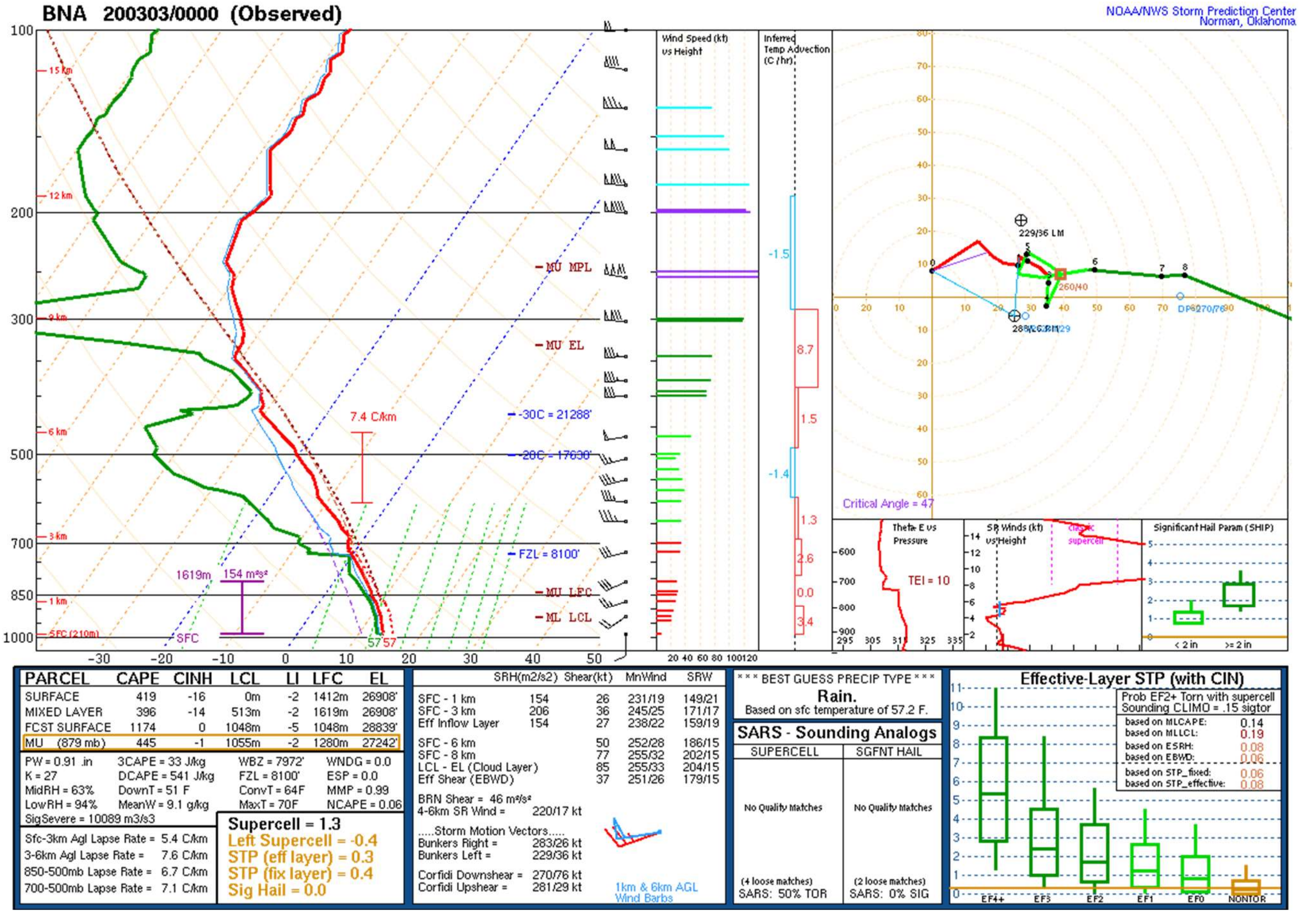

Figure 12: Observed Sounding From Nashville, Tennessee at 00Z on March 3, 2020 (6 PM CST on March 2, 2020) (SPC Severe Weather Event Review for Monday March 02, 2020).

<u>04Z (10 PM March 2nd): Mesoscale Maps</u>

At this time, the supercell that would produce multiple tornadoes and widespread damage across Tennessee was in Gibson County in West Tennessee and had a severe thunderstorm warning associated with it. A tornado was not ongoing at this point, but strong winds up to 60 mph were. These strong winds were supported by mesoscale conditions trending unstable across the area.

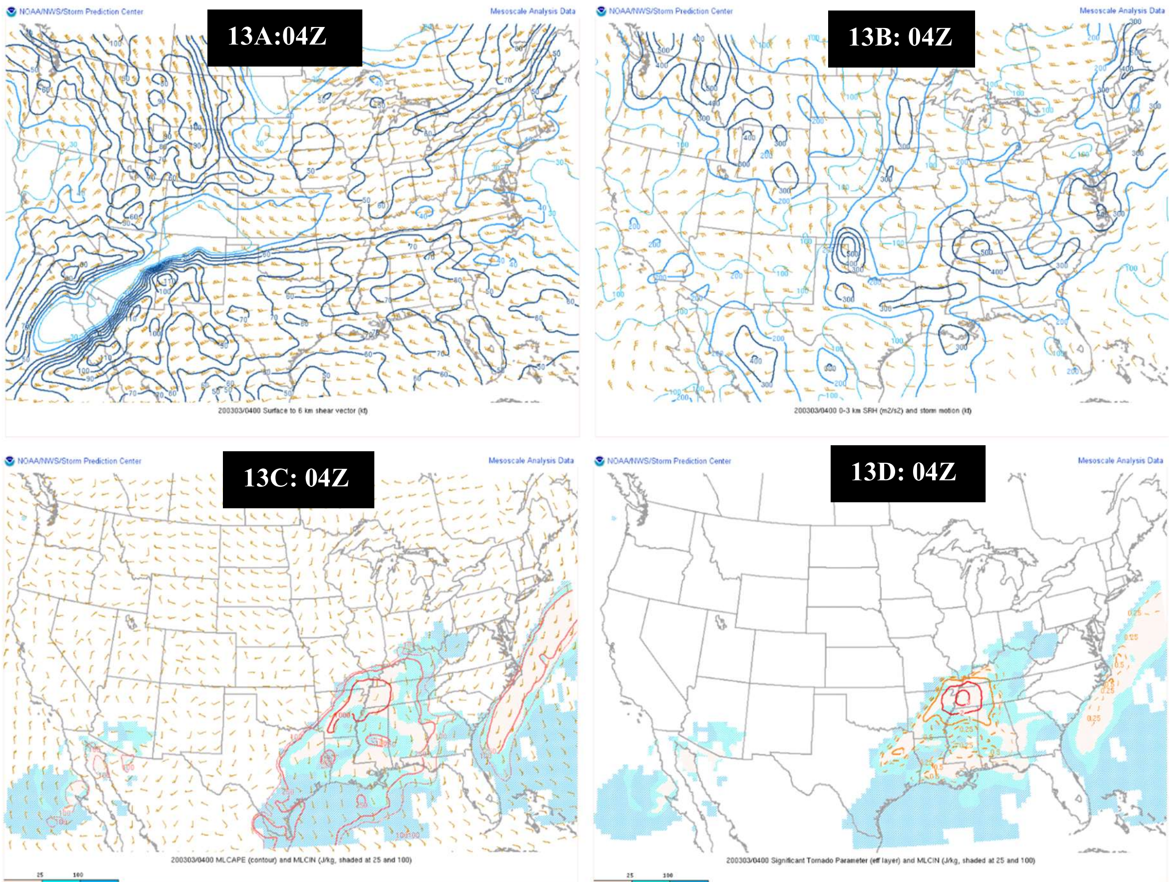

Figure 13: 04Z Mesoscale Maps (SPC Mesoscale Analysis): **13A.** Surface to 6 km Shear (Knots); **13B.** 0-3 km Storm Relative Helicity ($\frac{m^2}{s^2}$); **13C.** Mixed Layer CAPE ($\frac{J}{kg}$) & CIN ($\frac{J}{kg}$); **13D.** Significant Tornado Parameter.

The most noteworthy mesoscale features at this place and time were the 0 to 6 km shear vector having a value of 60 knots (Figure 13A), anything greater than 40 knots is considered to be supportive of supercells (NOAA's National Weather Service, n.d.). Another feature was the 0-

3 km storm relative helicity being 500 $\frac{m^2}{s^2}$ (Figure 13B), anything greater than 250 $\frac{m^2}{s^2}$ suggests an increased threat of tornadoes (NOAA's National Weather Service, 2015). The Mixed Layer CAPE being 1000 $\frac{J}{kg}$ (Figure 13C) is sufficient for strong to severe storms according to the NWS (NOAA's National Weather Service, 2015). Finally, the significant tornado parameter is between 2 and 3 (Figure 13D), with anything greater than 1 indicating and increased potential for significant tornadoes (NOAA's National Weather Service, 2015). Other values found were the lapse rate to be 7.5 $\frac{°C}{km}$, effective bulk shear to be 40 knots, and surface based CAPE close to 1000 $\frac{J}{kg}$, all indicating that there is some instability in the atmosphere at this time.

<u>0412Z (10:12 PM March 2nd): EF-1 Tornado in Gibson County</u>

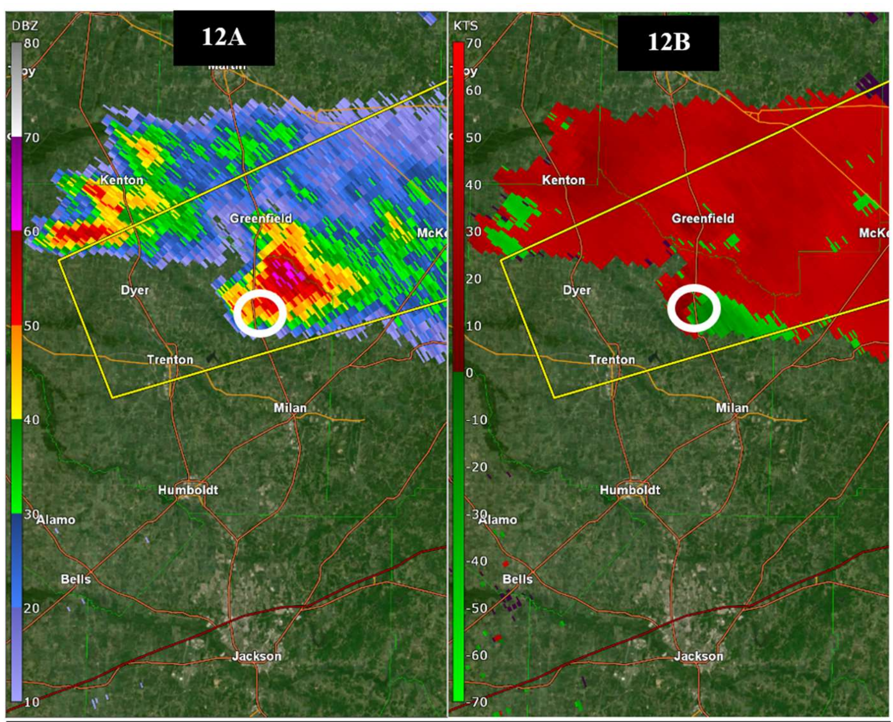

Figure 14: KNQA, Memphis, TN Radar Imagery at 0414Z just after an EF-1 Tornado Touched Down. **14A.** Base Reflectivity (dBZ); **14B.** Base Velocity (Knots).

According to the National Centers for Environment Information (NCEI), the first tornado to touch down was at 10:12 PM in Gibson County. This tornado was not warned by the National Weather Service. The latitude and longitude identified in the storm survey as the starting point of the tornado matches up with a slight hook on the radar reflectivity (Figure 14A) and a velocity couplet (Figure 14B). The mesoscale products maps from just 12 minutes earlier showed favorable conditions for tornadoes in this area. This tornado would only be classified as an EF-1, but it still did $250,000 worth of damage along the 7 miles that it traveled in 11 minutes with peak wind speeds of 95 mph (NCEI, n.d.).

0441Z (10:41 PM March 2nd): EF-2 Tornado in Carroll County

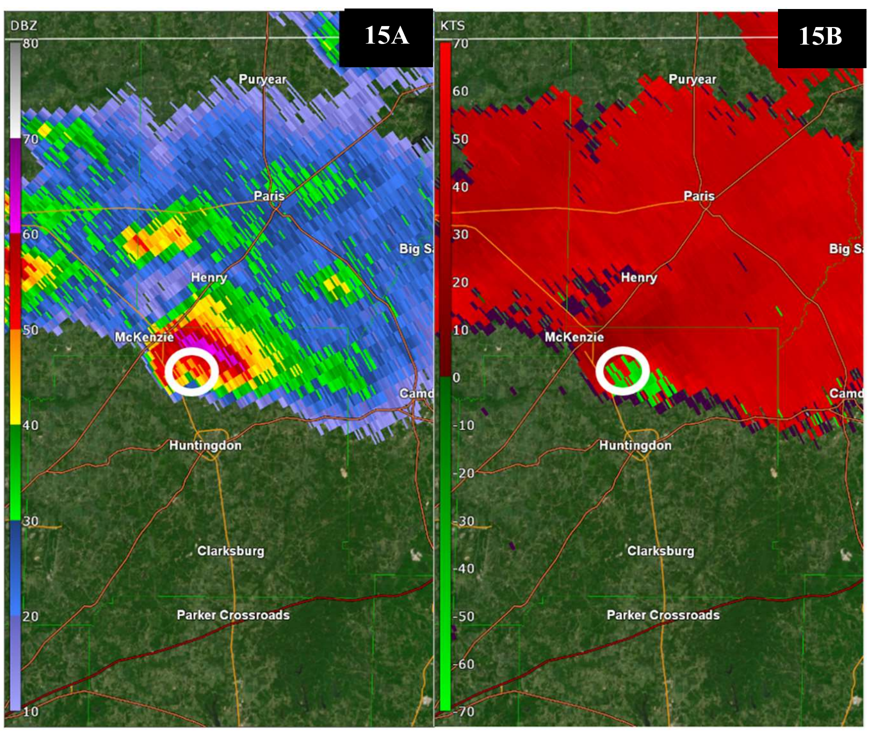

Figure 15: KNQA, Memphis, TN Radar Imagery at 0442Z just after an EF-2 Tornado touched down. **15A.** Base Reflectivity (dBZ); **15B.** Base Velocity (Knots).

The original tornado lifted in Gibson County at 10:23 PM, but it did not take long before it had cycled and touched back down again as an even stronger EF-2 tornado. The radar shows a more defined hook shape on the reflectivity (Figure 15A) and a velocity couplet (Figure 15B) indicating that rotation is ongoing in this area. This tornado was on the ground for 16 minutes, lifting at about 10:57 PM, for a total of 14.8 miles and resulting in $500,000 in damages (NCEI, n.d.).

0505Z (11:05 PM March 3rd): EF-2 Tornado in Benton County

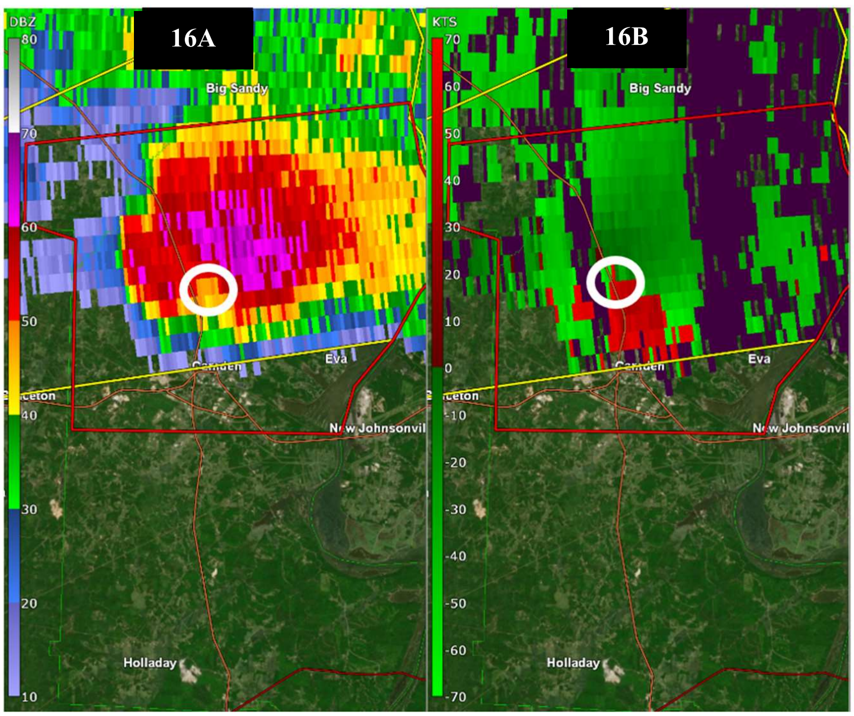

Figure 16: KNQA, Memphis, TN Radar Imagery at 0507Z just after an EF-2 Tornado touched down. **16A.** Base Reflectivity (dBZ); **16B.** Base Velocity (Knots).

Less than 30 minutes after the Carroll County tornado had lifted, another tornado was produced from this supercell. It first touched down close to 0505Z, in central Benton County. This storm was rated an EF-2 that was on the ground for about 15 minutes for 10 miles. The radar reflectivity (Figure 16A) does not show the hook echo as it did with the previous two tornadoes. This is likely due to the distance the storm is away from the Memphis radar as Benton County is the furthest eastern county in NWS Memphis's County warning area. However, the base velocity (Figure 16B) does show a couplet indicating that rotation is possible in the upper levels of the storm. This tornado continued into Humphreys County within the NWS Nashville CWA. Along its path, 1 fatality and 2 injuries occurred along with $1 million in property damage (NCEI, n.d.). This supercell would go on to produce a weaker EF-0 tornado in Eastern Humphreys County, before cycling once again as it made its way to Davidson County.

06Z (12 AM March 3rd): Mesoscale Maps

At 06Z, the supercell that had previously produced 5 tornadoes in Tennessee was in Dickson County. The storm was tornado warned at this point, but a tornado was not on the ground. However, the threat for tornadoes was not gone. In fact, the opposite was true. Comparing the 06Z mesoscale conditions to the 04Z, show an improving environment for the development of severe storms.

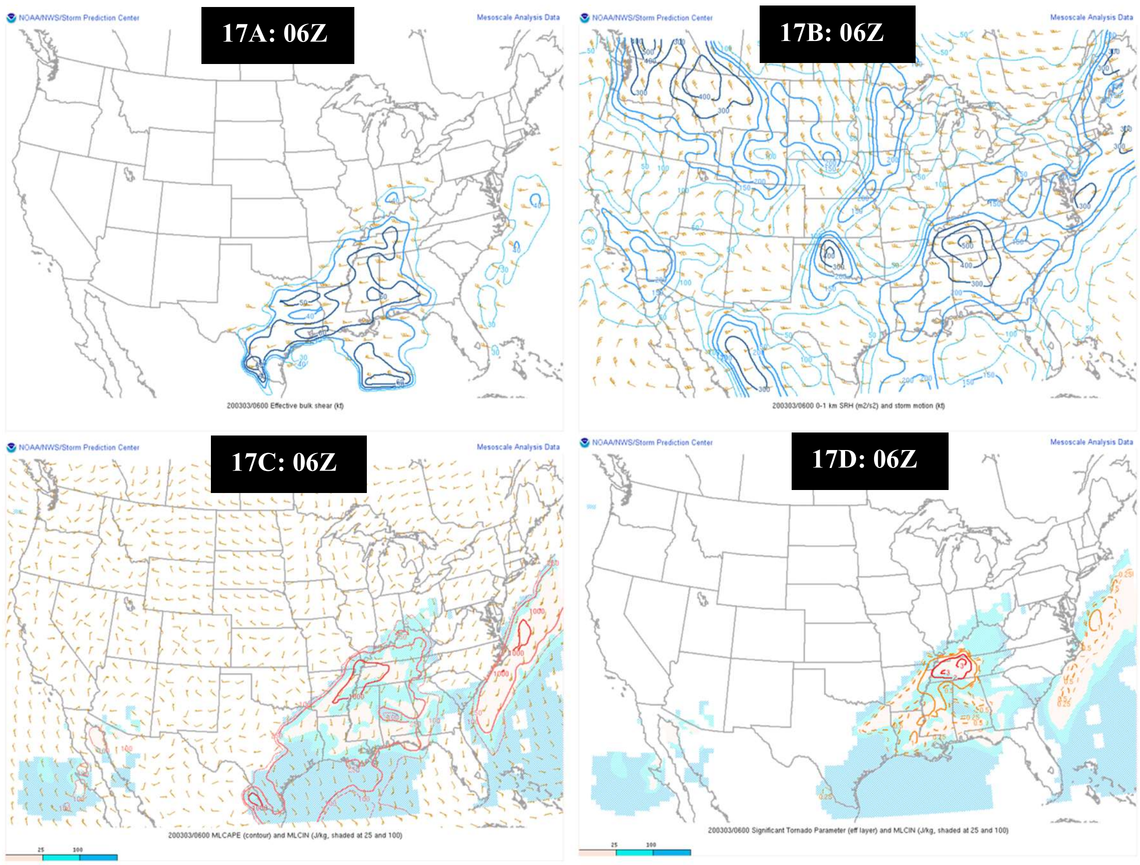

Figure 17: 06Z Mesoscale Maps (SPC Mesoscale Analysis): **17A.** Effective Bulk Shear (Knots); **17B.** 0-1 km Storm Relative Helicity ($\frac{m^2}{s^2}$,); **17C.** Mixed Layer CAPE ($\frac{J}{kg}$) & CIN ($\frac{J}{kg}$); **17D.** Significant Tornado Parameter.

The most notable mesoscale conditions were the effective bulk shear being 50 knots (Figure 17A), the 0-1 km storm relative helicity showing a bullseye on the area where the supercell was located with a value close to 500 $\frac{m^2}{s^2}$ (Figure 17B), the mixed layer CAPE shows a value of 1000 $\frac{J}{kg}$ stretching over to the location of the supercell along with low values of CIN near 25 $\frac{J}{kg}$ (Figure 17C). The significant tornado parameter shows a value of 3 near the area of the supercell (Figure 17D). Other noteworthy mesoscale features were the surface to 6 km shear being 60 knots, the lapse rate being 6 $\frac{°C}{km}$, the 0-3 km storm relative helicity being 500 $\frac{m^2}{s^2}$, and the surface based CAPE being near 250 $\frac{J}{kg}$ along with a CIN close to 100 $\frac{J}{kg}$. The CAPE was likely lower at this time due to the lack of daytime heating. Convective energy tends to decrease further into the evening due to the lack of daytime heating and the resulting cooling surface temperatures. Despite the low values of surface based CAPE and lapse rates, the other mesoscale conditions exceeded the values observed at 04Z, showing the improving mesoscale conditions for the development of tornadoes.

0632Z (12:32 AM March 3rd): Davidson and Wilson County EF-3 Tornado

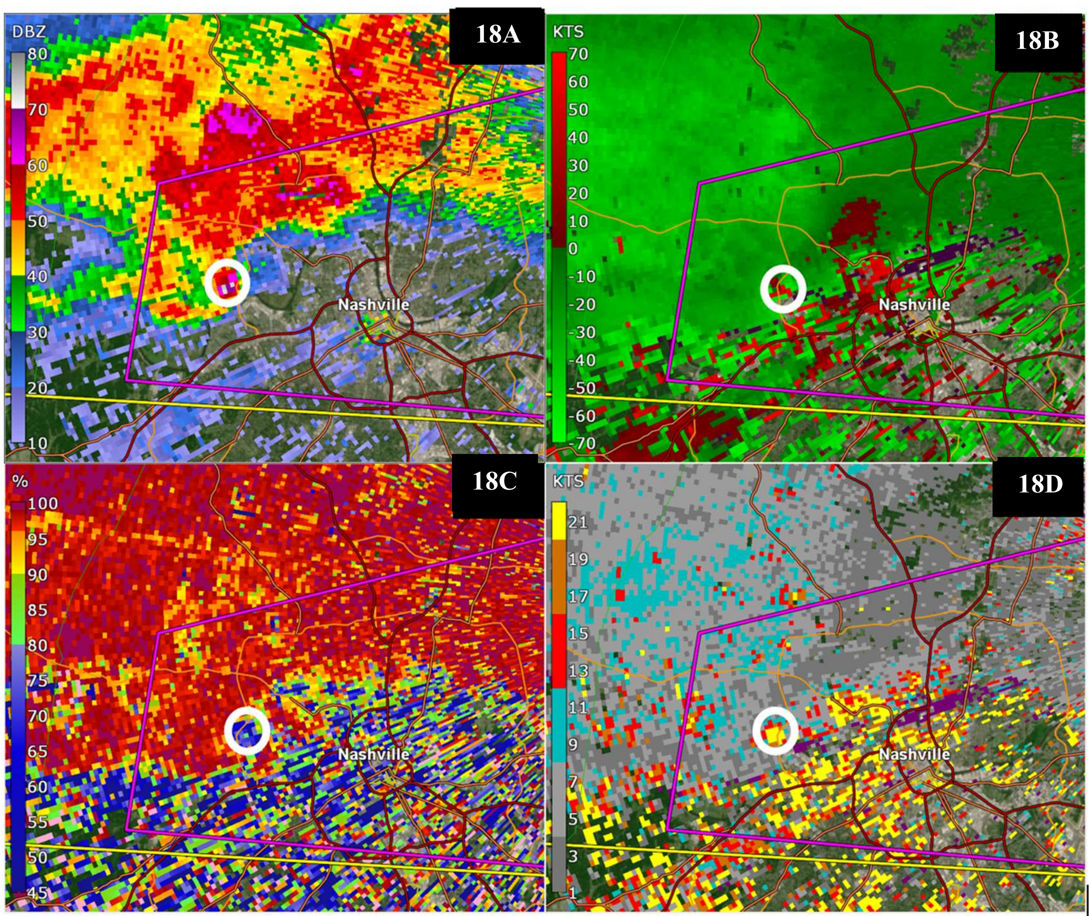

Figure 18: KOHX, Nashville, TN Radar Imagery at 0636Z just after an EF-3 Tornado touched down. A confirmed tornado warning is displayed by the Pink/Purple Warning Outline. **18A.** Base Reflectivity (dBZ); **18B.** Base Velocity (Knots); **18C.** Correlation Coefficient (%); **18D.** Spectrum Width (Knots).

At 0632Z, the supercell produced its strongest tornado of the track so far, an EF-3 in Davidson County, home of Nashville. On radar imagery taken a few minutes after the initial touchdown, it is clear that this tornado is very strong. A very well defined hook with higher values of reflectivity peaking near 75 dBZ is seen (Figure 18A). Additionally, a tight velocity couplet (Figure 18B) is present with peak wind values going towards the radar close to 60 knots and going away from the radar near 63 knots for a combined wind speed of 123 knots or close to 142 miles per hour. A low correlation coefficient (Figure 18C), indicative of a debris ball, is also present with values as low as 34% observed. Values of spectrum width (Figure 18D) are peaking near 37 knots, indicating a strong updraft is present on this radar imagery. All of these parameters allow for the National Weather Service to issue a confirmed tornado warning. This tornado was on the ground for 47 minutes and a total 60 miles! Stretching all the way from Western Davidson County to Eastern Wilson County. As it tracked through a very heavily populated area, 5 people were killed along with 220 injured (NCEI, n.d.). Close to $1.5 billion in damages were reported along this track alone. This tornado would lift in Eastern Wilson County at 0719Z (1:19 AM) to begin the cycling process once again. It would then touch down as a brief EF-1 tornado in Western Putnam County before starting the cycling process once again as the supercell moved closer to Cookeville.

0748Z (1:48 AM March 3rd): Putnam County EF-4 Tornado

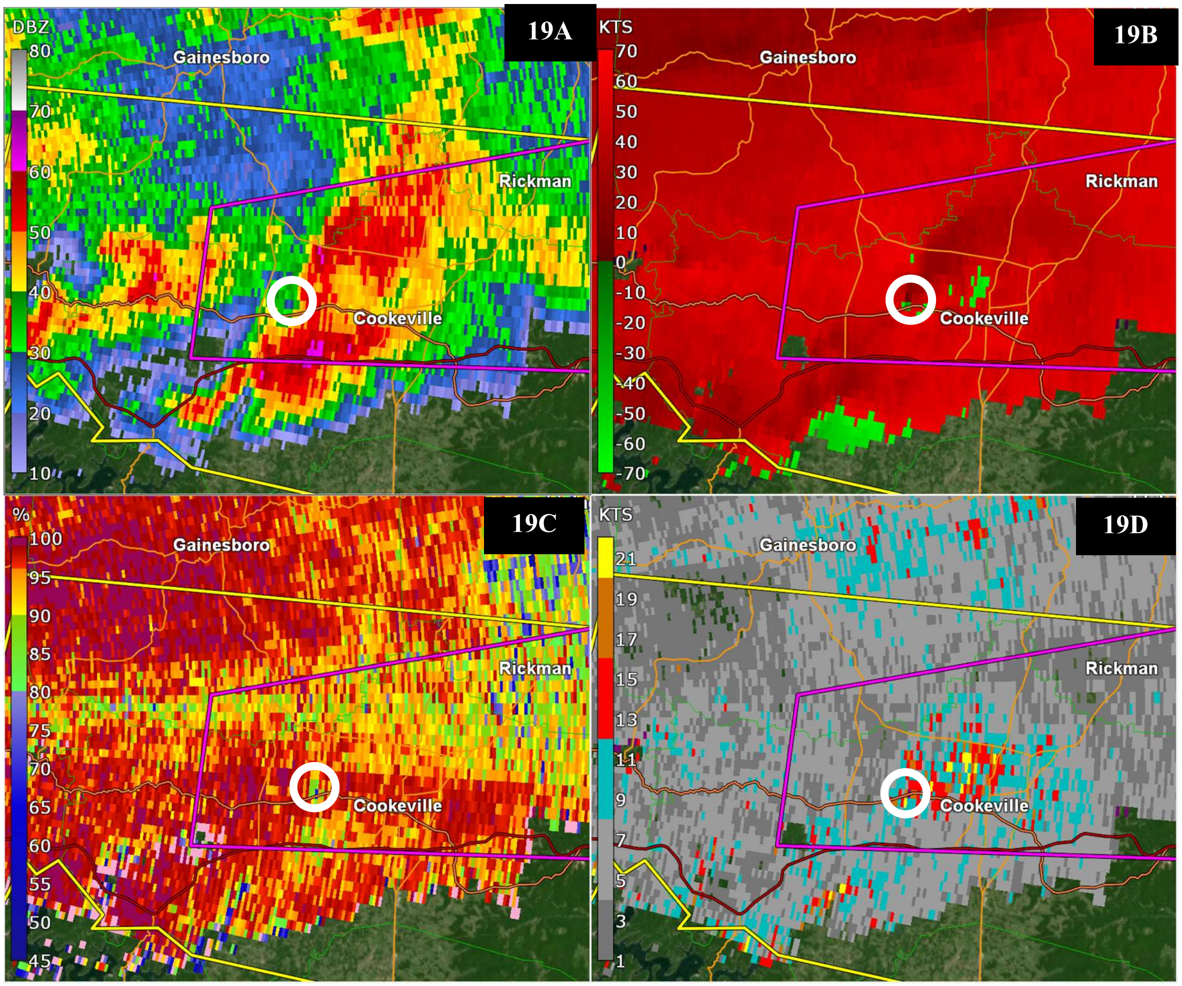

Figure 19: KOHX, Nashville, TN Radar Imagery at 07:53 Z just after an EF-4 Tornado touched down west of Cookeville. **19A.** Base Reflectivity (dBZ); **19B.** Base Velocity (Knots); **19C.** Correlation Coefficient (%); **19D.** Spectrum Width (Knots).

At 0748Z, the supercell that had already caused so much destruction across Tennessee produced its strongest tornado of the night: an EF-4 tornado in Western Putnam County. Radar imagery shows the textbook hook on reflectivity (Figure 19A) with peak values near 62 dBZ, a tight velocity couplet (Figure 19B) with windspeeds near 62 knots going towards the radar and 63 going away, a low correlation coefficient (Figure 19C) near 68% over the area of suspected rotation, and higher spectrum width values (Figure 19D) near 30 knots indicating a strong updraft. This tornado was only on the ground for 8 minutes for a total of a little over 8 miles across western Putnam County, but it was the most devastating of the evening, resulting in 19 deaths, 87 injuries, and $100 million in property damage (NCEI, n.d.). The magnitude of this tornado can be seen on radar imagery after it had been on the ground for its entire track. Imagery from 0758Z shows correlation coefficient values as low as 21% (Figure 20), indicating that there is significant shape and orientation variation between the items that the radar is picking up on. The supercell weakened after this tornado. It did not produce another tornado until 30 miles eastward in Cumberland County, where it produced an EF-2 tornado.

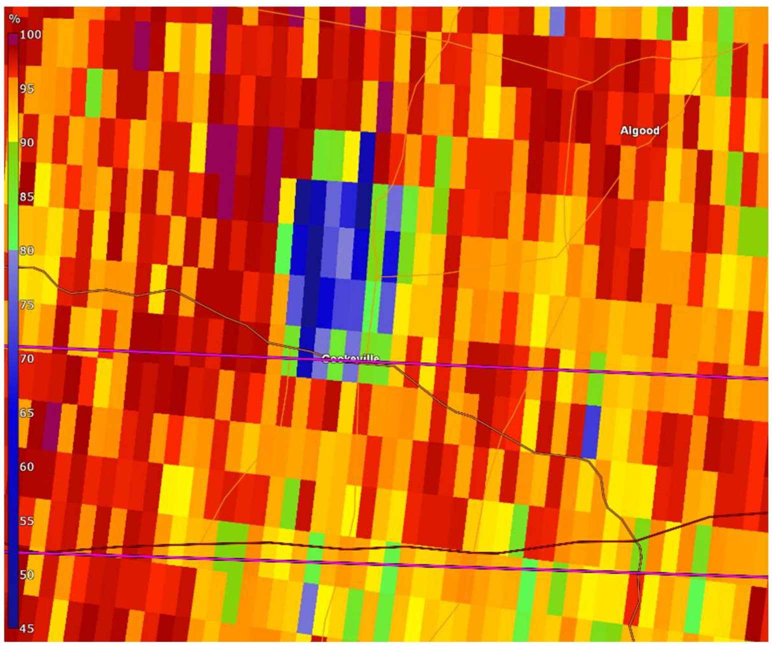

Figure 20: KOHX, Nashville, TN Radar Correlation Coefficient (%) values at 0757Z about 10 minutes an EF-4 Tornado touched down west of Cookeville.

<u>08Z (2 AM March 3rd): Mesoscale Maps</u>

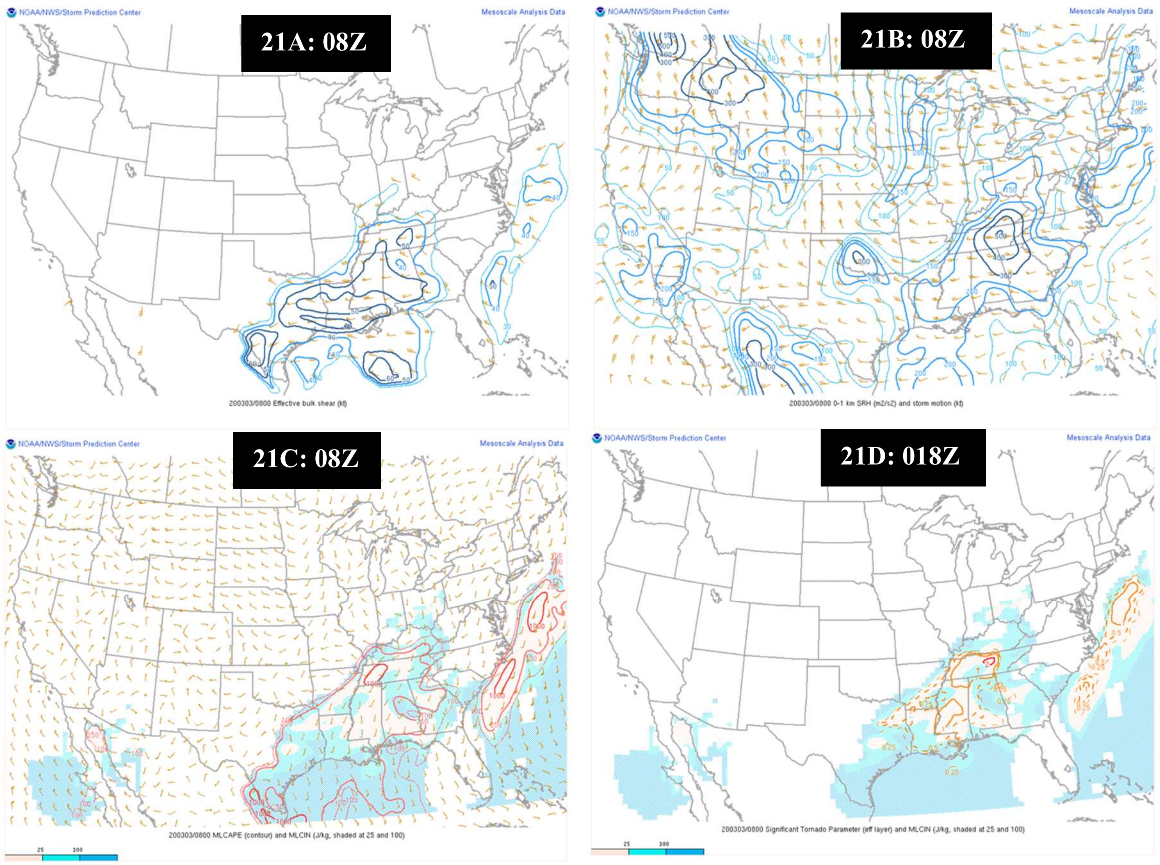

Figure 21: 08Z Mesoscale Maps (SPC Mesoscale Analysis): **21A.** Effective Bulk Shear (Knots); **21B.** 0-1 km Storm Relative Helicity ($\frac{m^2}{s^2}$); **21C.** Mixed Layer CAPE ($\frac{J}{kg}$) & CIN ($\frac{J}{kg}$); **21D.** Significant Tornado Parameter.

The mesoscale conditions seen at 08Z showed conditions that favored the development of severe storms, and even strong tornadoes. Some notable conditions to mention include the effective bulk shear being 50 knots (Figure 21A), the 0-1 km storm relative helicity being 500 $\frac{m^2}{s^2}$ (Figure 21B), the mixed layer CAPE being 250 $\frac{J}{kg}$ and a small CIN of less than 25 $\frac{J}{kg}$ (Figure 21C), and a significant tornado parameter value of 2 (Figure 21D). Other features worth mentioning include the surface to 6 km shear vector having a value of 60 knots, lapse rate being near 6.5 $\frac{°C}{km}$, 0-3 km storm relative helicity being 500 $\frac{m^2}{s^2}$, and the surface based CAPE being near 250 $\frac{J}{kg}$ with surface based CIN near 100 $\frac{J}{kg}$.

These conditions point to the possibility of some stronger storms, but other than the significant tornado parameter being high, none of these other features point towards the possibility of an EF-4 tornado, particularly examining the low CAPE values and higher CIN values. Research by Broyles (2002) found that many violent tornadoes in the Southeast form when CAPE values were lower, but winds were strong. Out of 12 violent tornadoes, EF-4 to EF-5 strength, the study found that the average wind speeds in the Southeast at the 500 mb level were 63.4 knots (Broyles et. al. 2002). Figure 11C shows that the wind speeds at this level at the time of the Cookeville tornado were about 65 knots, enough to compensate for the weaker CAPE values according to Broyle.

<u>0825Z (2:25 AM March 3rd): Cumberland County EF-2 Tornado</u>

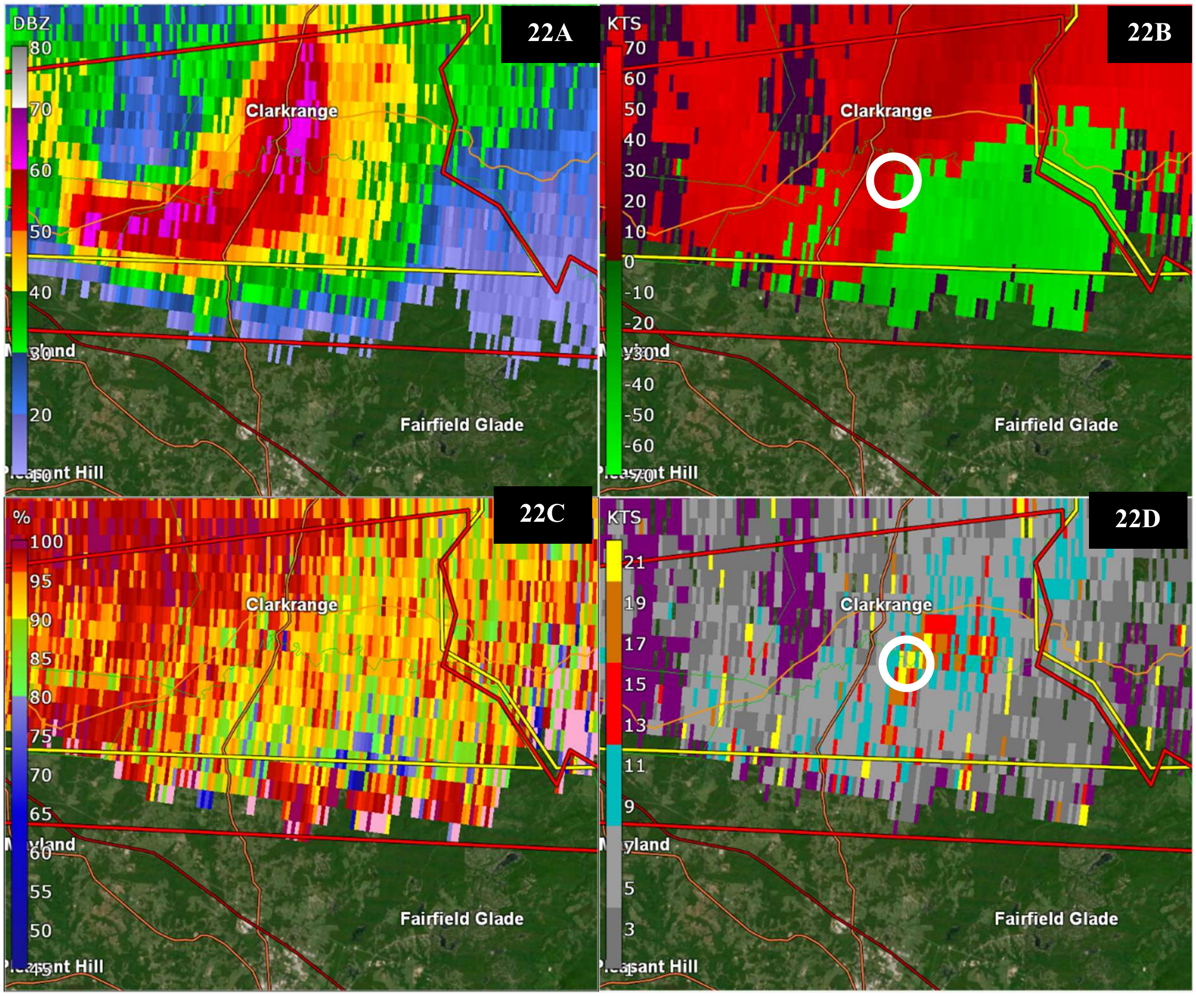

Figure 22: KOHX, Nashville, TN Radar Imagery at 0824Z just before an EF-2 Tornado touched down in Cumberland County. **22A.** Base Reflectivity (dBZ); **22B.** Base Velocity (Knots); **22C.** Correlation Coefficient (%); **22D.** Spectrum Width (Knots).

The final substantial tornado produced by this supercell was in Northen Cumberland County at 825Z. This tornado was rated an EF-2. The radar reflectivity does not show the hook echo that is expected, but this is likely due to the distance away from the radar that Cumberland County is. The reflectivity does show some higher values near 61 dBZ that line up with a velocity couplet, indicative of rotation (Figure 22A). Velocity values estimated by the radar are 60 knots going towards the radar and 51 knots going away (Figure 22B). Additionally, the correlation coefficient values are not impressive at this time as the tornado would not touch down for another minute (Figure 22C), but spectrum width values were high being near 24 knots (Figure 22D). This storm was on the ground for about 10 miles. No fatalities or injuries were reported but over half of a million dollars in damage was done by this tornado (NCEI, n.d.). After this tornado lifted, the supercell continued along its eastern track for the next hour before dropping a weak EF-0 tornado in Morgan County in East Tennessee. This tornado was only on the ground for about 4 miles over the course of 2 minutes. After this tornado lifted, the supercell did not produce any more tornadoes as it progressed eastward.

Summary/Conclusions

Ultimately, the analysis of the synoptic conditions, mesoscale conditions, and tornado tracks completed throughout this research showed that several mesoscale and synoptic conditions did change from the forecast, allowing for the development of this devastating supercell and its continued strengthening as it moved across the state of Tennessee. The SPC and NWS offices were predicting that conditions would not be very favorable for the development of tornadoes across Tennessee, even in a NWS discussion issued 1 hour before the first tornado formed, due to the lack of daytime heating expected to keep the severe threat low. However, other mesoscale and synoptic conditions seemed to compensate for the lack of daytime heating.

At 04Z, synoptic and mesoscale conditions showed a trough over West Tennessee, warm air advection, strong upper level winds between 60 and 80 knots, vorticity advection values near 16 knots, 0 to 6 km wind shear near 60 knots, 0-3 km storm relative helicity values near 500 $\frac{m^2}{s^2}$, mixed layer CAPE near 1000 $\frac{J}{kg}$, and a significant tornado parameter between 2 and 3. These values are impressive and supportive of severe storms and tornadoes. Looking at these values now, it is not a surprise that two EF-2 tornadoes, two EF-1s, and one EF-0 would touchdown over Gibson, Carroll, Benton, and Humphreys Counties within the next two hours.

At 06Z, the synoptic and mesoscale conditions showed improving atmospheric conditions for tornadoes in the area of the supercell. The trough is now located in Middle Tennessee and has become more negatively tilted, indicating that the low pressure system has intensified. Additionally, warm air advection has become more pronounced, the upper level winds is near 80 knots, vorticity advection is near 12 knots, effective bulk shear is near 50 knots, 0-3 km storm relative helicity values are near 500 $\frac{m^2}{s^2}$, mixed layer CAPE values are near 1000 $\frac{J}{kg}$, and the supercell is located in an area where the significant tornado parameter is 3. The improving atmospheric conditions are seen through the strengths of tornadoes touching down and the distances of the tracks. The costliest tornado of the evening went through Nashville in Davidson County then through the suburbs of Mount Juliet and Lebanon in Wilson County, staying on the ground for 47 minutes for a distance of 60 miles. Along its 60 mile track, 5 people were killed, 220 people were injured, and near $1.5 billion in property damages were reported. A much weaker EF-0 occurred after the tornado had lifted in Wilson County and cycled before briefly touching down in Smith County.

At 08Z, the synoptic and mesoscale conditions continued to show improved conditions for the development of severe storms. At this time, the trough continues to be negatively tilted and is now over Middle Tennessee. Substantial warm air advection, upper level winds near 65 knots, and vorticity advection values are near 15 knots in the area of the supercell. The effective bulk shear is near 50 knots, 0-1 km storm relative helicity values are near 500 $\frac{m^2}{s^2}$, mixed layer CAPE values are near 250 $\frac{J}{kg}$, and the supercell is located in an area where the significant tornado parameter is 3. While the CAPE values are lower than would be expected for a tornado, research by Broyles (2002) has found that the strong wind speeds present at this time were more than enough for significant tornadoes to occur. The strongest tornado in the life of this supercell was produced just before 08Z in Western Putnam County. This tornado was rated an EF-4 and was on the ground for only 8 miles over the course of 8 minutes, but it resulted in 19 deaths, 87 injuries, and $100 million in damages along its track. Even after reaching EF-4 strength and rising back off of the ground, the tornado would cycle two more times, producing EF-2 damage in Cumberland County and EF-0 in Morgan County before the supercell would be done producing tornadoes.

While the lack of daytime heating was expected to keep the severe weather threat for Tennessee low, the mesoscale and synoptic conditions mentioned above seemed to compensate for the instability that is usually created from heating during the day. One particular condition that helped drive this tornadic supercell was the high wind shear values. This thought lines up with research completed by Broyles (2002) about significant tornadoes in the South. One main takeaway from this research is that even though higher instability occurs during the day and early evening as a result of sunlight, wind shear can be just as important to the development of tornadoes, particularly for nocturnal events.

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