A Synthetic Dual-Doppler Analysis of the 03 March 2020 Nashville, Tennessee Tornado

Joshua Lambert Huggins

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A Synthetic Dual-Doppler Analysis of the 03 March 2020 Nashville, Tennessee Tornado

by

Joshua Lambert Huggins

An Honors Capstone

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for the Honors Diploma

to

The Honors College

of

The University of Alabama in Huntsville

01 May 2022

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Professor, Department of Atmospheric and Earth Science

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Student Date
Joshua L. Huggins 04/29/2022

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Department Chair Date
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04/29/2022

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Honors College Dean Date
William Wilkerson

Date: 2022.04.29 13:25:03 -05'00'
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Joshua L. Huggins

Student Name (printed)

Joshua L. Huggins

Student Signature

04/29/2022

Date
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Dedication

I would like to dedicate this Capstone Project to the people of Central Tennessee who were impacted by this tornado outbreak and to those who lost their lives as a result of these storms. I hope that my research on this storm may one day help improve forecasting and warning times to better protect the loss of life and property from some of the most vicious phenomena that Mother Nature offers.

I would like to thank Dr. Kevin Knupp and the Earth System Science Center (ESSC) for allowing me to work on this project to not only enhance my knowledge of the atmosphere, but also to expose myself to numerous types of softwares used in the meteorological community. I would also like to thank Dr. Robert Griffin, Associate Dean of the College of Science, for hiring me for my first job in the ESSC back in 2018 that created the stepping stones to me working for Dr. Knupp. I owe much gratitude to Dr. Sarah Stough and Adam Weiner for their diligent assistance on my code during the data gridding process that stumped me for over a month. I would like to thank Dr. Carlanna Hendrick, former professor of History at the South Carolina Governor’s School for Science and Mathematics for her guidance on my college decision process and assisting me in realizing my passions. Lastly, I would like to thank those who have helped and supported me both on this project and during my time at The University of Alabama in Huntsville.
Abstract

During the overnight hours between 02-03 March 2020, a discrete, high-precipitation supercell spawned numerous tornadoes across much of Central Tennessee. The city of Nashville took a direct hit from an EF-3 tornado with peak winds of 140 miles per hour within the city limits. Numerous Citizen Weather Observing Program (CWOP) Stations recorded pre-storm surface temperatures between 60-65°F and dew point temperatures between 52-56°F. Radar data from the National Weather Service Weather Surveillance Radar 1988-Doppler (WSR-88D) at the Nashville office and upper-air soundings from the Severe Weather Institute - Radar and Lightning Laboratories at the University of Alabama in Huntsville were used for this project to better understand the atmospheric environment. A Synthetic Dual-Doppler (SDD) Analysis is in the process of being performed on this tornado to attempt to retrieve low-level flow within the mesocyclone and adjacent regions of the storm and structure a three-dimensional representation of the winds in the lowest part of the mesocyclone. These representations will assist in defining the nature of the Boundary Layer flow into the storm. This analysis utilized the SoloIII Radar Editing Software and the Custom Editing and Display of Reduced Information in Cartesian Space (CEDRIC) Editing Software from the National Center for Atmospheric Research Earth Observing Laboratory. The Nashville tornado is a prime case for an SDD Analysis as it tracked within ten statute miles of the WSR-88D, had a large storm motion vector (25-30 ms⁻¹), and maintained a relative steady-state strength. This analysis will follow the techniques used by Murphy and Knupp (2013) and several others during the closest passage of the tornado to the WSR-88D between 0636Z to 0712Z.
Introduction

The Day 1 Storm Prediction Center (SPC) Outlook for 03 March 2020 featured much of Central and Eastern Tennessee in a slight risk for severe weather. Shortly after midnight on 03 March, a tornado formed near John C. Tune Airport on the west side of Nashville, Tennessee. This tornado would reach winds of 140 miles per hour and tear a path of destruction sixty miles through Nashville and its eastern suburbs. The tornado, henceforth referenced as the Nashville tornado, would be but one of nine tornadoes to strike Central Tennessee that night, killing five people and causing over one billion dollars in damage.

Several teams from The University of Alabama in Huntsville (UAH) Department of Atmospheric and Earth Science (AES) traveled to areas south of Nashville to perform crucial meteorological research during the tornado outbreak. Students from the Severe Weather Institute - Radar and Lightning Laboratories (SWIRLL) at UAH were stationed in locations such as Brentwood, Culleoka, Lawrenceburg, and Pulaski in south central Tennessee. Shortly after the tornado crossed through downtown Nashville, a weather balloon sounding from a SWIRLL team in Brentwood closely followed the system in its near due-east track.

The Nashville tornado created a unique research opportunity that does not occur often, in that the storm passed within a short distance of the National Weather Service (NWS) Weather Surveillance Radar - 1988 Doppler (WSR-88D) in Old Hickory, Tennessee. Storms that pass this close to a WSR-88D withhold the potential to undergo a Synthetic Dual-Doppler (SDD) Analysis in which a single-Doppler radar is used and manipulated to examine low-level winds in and around a mesocyclone.
In order for an SDD Analysis to be performed, three main criteria must be met. Murphy and Knupp (2013) published that in addition to a close passage of a storm to a WSR-88D (typically within twenty to forty kilometers), storms must also have “relative steadiness…during passage…[and a] large motion vector” (602). This large storm motion vector is a subjective value, but must “be aligned at an angle sufficiently large that the difference in viewing angles of the system is great enough for the horizontal wind field to be resolved accurately” (Bluestien et al. 1994). Klimowski and Marwitz (1992) defined this angle to be at least 30°, however other studies do not define a set value.

The Nashville tornado meets all three criteria set forth by Murphy and Knupp, Bluestien, and Klimowski, et al. by passing within fifteen statute kilometers of a WSR-88D, remained relatively steady-strength during this passage, and contained a large storm motion vector (SMV) of 25-30 meters per second (ms\(^{-1}\)). This project will complete an SDD Analysis via radar data editing and gridding before being imported into the CEDRIC (Custom Editing and Display of Reduced Information in Cartesian Space) software to dissect low-level winds into and around the mesocyclone of the Nashville tornado.
Meteorological Background

A typical storm requires three main atmospheric ingredients for its initiation: lifting, instability, and moisture. These ingredients may come from a variety of sources that make storms possible across the globe. Atmospheric lifting, or a lifting mechanism, is caused by air that is forced upward into the atmosphere. Interactions with mountain ranges or convergence of warmer air over cooler air, among others, can force air to rise. Instability, as defined by Meteorologist Jeff Haby from the National Oceanic and Atmospheric Administration (NOAA), is the “...condition in which air will rise freely on its own due to positive buoyancy” (Haby: Instability n.d.). The main atmospheric parameter used to assess instability is the Convective Available Potential Energy (CAPE) of a theoretical column of air. CAPE is a value of the amount of energy available for an air parcel to rise. In short, the higher the CAPE value, the greater the instability. The last main ingredient is moisture, which is a measure of available water vapor in the atmosphere. In the United States, areas along the coast have a greater amount of moisture due to their proximity to large bodies of water and typical flow of winds. Storms with these main ingredients typically have a life-span of up to one hour and are often a single cell type.

Multicell storms and supercell storms, like the one that produced the Nashville tornado, require a key fourth ingredient to support their longevity and strength. In order for more severe and longer-lived thunderstorms to form, “...strong speed and directional storm relative windshear” must be available across a defined region (Haby: Thunderstorms n.d.). Windshear is the changing of both wind speed and direction with height that can tilt the updraft of a thunderstorm. The 0 to 6 kilometer (km) wind shear value, or “bulk shear”, is an important factor when considering the potential for long-lived thunderstorms and supercells. Typical bulk shear
values exceeding 25 ms\(^{-1}\) are sufficient for producing these types of storms. Further storm type characteristics and backgrounds are outside the scope of this project.

The first indication for the potential for severe weather across Tennessee occurred with the Day 3 Convective Outlook released by the SPC on 29 February 2020. A region covering western Tennessee and the Mississippi River Valley were denoted as having a twenty percent chance of severe weather during the overnight hours between 02 March and 03 March. Cities such as Memphis and Jackson, Tennessee were included in this risk, but Nashville was not [Figure 1]. A strong, upper-level low pressure system was expected to trek east-southeastward across the United States between 29 February and 03 March, while southerly winds from the Gulf of Mexico were expected to amplify available atmospheric moisture over portions of western and central Tennessee. The advancing low-pressure system with abundant moisture, combining over areas with available lifting from a frontal boundary, caused the SPC to first put out this outlook for the threat for severe weather.

The Day 2 Outlook released on 01 March expanded the threat for severe weather further east into Central Tennessee and included the city of Nashville [Figure 2]. The SPC noted in their mesoscale discussion that “wind profiles with 40 kt [knots] 0-6 km shear will support some supercells…[and] a tornado or two cannot be ruled out…but is conditional on the sufficient boundary layer destabilization” (SPC 2020). With the three main ingredients in place, the final ingredient needed for longer-lived thunderstorms was expected to come into play by the evening of 02 March. The discussion further lists the limiting factors that may hinder thunderstorm growth based on variability in the models. Even still, the SPC noted that an increase to a slight risk (forty percent chance for severe thunderstorms) may occur by the Day 1 Outlook.
Figure 1: Day 3 Categorical Outlook for 03 March 2020 issued by the Storm Prediction Center (SPC) on 29 February 2020

Figure 2: Day 2 Categorical Outlook for 03 March 2020 issued by the SPC on 01 March 2020
By midday on 02 March 2020, the SPC upgraded Western and Central Tennessee into a slight risk for severe weather in the Day 1 Outlook [Figure 3]. Some of the limiting factors mentioned in the Day 2 Outlook had begun to lessen, increasing the threat across Tennessee. As low-level shear (typically defined below 850 millibars (mb)) was expected to increase, the SPC noted that a “low-end tornado threat” could occur (SPC 2020).

By nightfall on 02 March, storms had begun to initiate ahead of the advancing low-pressure system as most of the limiting factors of development had vanished. All four necessary ingredients combined along the middle Mississippi River Valley near the Tennessee/Missouri border and supported the threat for severe weather. The SPC upgraded portions of Western Tennessee to a five percent tornado outlook, relatively low but in line with the expected threat [Figure 4]. These risk assessments remained consistent during the overnight hours into 03 March.

![Figure 3: Day 1 Categorical Outlook for 03 March 2020 issued by the SPC on 02 March 2020](image-url)
Figure 4: Day 1 Tornado Outlook for 03 March 2020 issued by the SPC on 02 March 2020
The Atmospheric Environment

In order to better understand the progression of storms over a given area, one must first look at the atmospheric conditions. Surface data can be easily accessed by the public through the use of Automated Surface Observing Systems (ASOS) or Automated Weather Observing Systems (AWOS) stations. ASOS and AWOS stations are most commonly found at airports, and collect a variety of data from temperature and humidity to pressure. Several ASOS/AWOS sites were directly impacted by the severe storms on the night of 02 March, including John C. Tune Airport and Nashville International Airport. These stations were operational the night of the tornado and yielded valuable data for future forecasting. In addition to ASOS/AWOS stations, several students from UAH SWIRLL conducted weather balloon launches across south central Tennessee to better dissect the atmospheric environment. Further atmospheric data was obtained from Civilian Weather Observer Program (CWOP) stations within a fixed thirty mile east-west radius of downtown Nashville. The most valuable of these CWOP stations was Station E6276 located on the campus of Vanderbilt University. This CWOP site had one-minute averaged data of temperature, dew point temperature, pressure, wind speed and wind direction. Due to the data contamination from the surrounding high rise buildings of Nashville, site E6276 was excluded from the final portions of this project.

Data from Nashville International Airport (KBNA) at 6:00 p.m. local time on 02 March showed surface temperatures near 14 degrees Celsius (°C) with dew point temperatures slightly below 14°C [Figure 5]. In general, dewpoints of at least 15°C are required for thunderstorm development and enhancement, but are still possible in slightly less-moist environments (Haby: Thunderstorms). Higher dewpoint temperatures play a major role in thunderstorm development
in that higher temperatures increase atmospheric instability while providing ample moisture to a region. Precipitation had moved into Nashville by this time as is evident on the 00Z Sounding (6:00 p.m. local time - more on time conversions later) from KBNA below 2.5 km [Figure 5]. This influx of precipitation should help temporarily stabilize the atmosphere and theoretically reduce the severe weather threat for Central Tennessee.

Figure 5: 6:00 pm Central Standard Time Sounding from Nashville International Airport on 02 March 2020
Temperatures near 14°C are common for Central Tennessee during the early evening hours in early March (NWS n.d.). Several CWOP stations along Interstate 40 recorded temperatures similar to the ASOS station at KBNA, with all stations decreasing to near 10°C by midnight. These temperature agreements further validate the relatively cool temperatures present for thunderstorm formation. Several other meteorological parameters were studied to better understand how a strong tornado formed in an environment with cool temperatures. CAPE, bulk shear, Storm Relative Helicity, and height of the Lifting Condensation Level (LCL) were analyzed to assist in determining the environmental favorability for thunderstorms. Storm Relative Helicity (SRH) is a measure of the spin in the atmosphere, while the LCL is the point where an air parcel becomes saturated. Lower LCL heights can support a warming trend that may assist in tornado development.

The 6:00 p.m. sounding from KBNA yielded a Most Unstable CAPE (MUCAPE) value of 445 Joules per kilogram (Jkg⁻¹), with a bulk shear value of 50 knots. Typical MUCAPE values needed for supercell propagation often exceed 1,000 Jkg⁻¹, but was less than half that value in the pre-storm environment in the hours leading up to the tornado. These values represent a “high shear, low CAPE” scenario that is common in the Southeastern United States during the cool season (November - March). Murphy and Knupp (2013) further expand on the reasoning behind why this scenario is more common in the Southeast. LCL heights below 1,000 meters and SRH values exceeding 150 meters squared per second squared (m²s⁻²) supported the continued threat for severe weather as more air parcels became saturated and further allowed for some nighttime warming over the state of Tennessee.
The Nashville Supercell

Shortly after 9:00 pm local time on 02 March, a discrete supercell thunderstorm formed near the Mississippi River in Arkansas and moved east into Tennessee near the town of Dyersburg. With ample moisture and shear, the storm began to strengthen as the newly-formed cold pool ahead of the main convection acted as a boundary that allowed more parcels to rise, increasing the atmospheric instability. The storm would trek nearly due east across Tennessee on a collision course with Nashville. Four tornadoes spawned from this supercell before the system moved into Davidson County near midnight. As the storm approached Nashville, a fifth tornado formed and touched down in Bells Bend at 12:32 a.m. local time on 03 March, ten miles west of downtown. By 12:41 a.m., the tornado had rapidly strengthened and struck downtown Nashville with winds exceeding 120 miles per hour (mph). WSR-88D data from the National Weather Service in Nashville (KOHX) at 12:41 a.m. was plotted in GR2Analyst and showed a defined hook echo in reflectivity and a tight velocity couplet indicative of strong rotation [Figure 6].

Since the dual-polarization upgrade of all WSR-88D radars in 2013, meteorologists have been able to use the Correlation Coefficient (CC) parameter to further identify probable ongoing tornadoes on radar. CC measures the similarity of particles in the atmosphere with their relative shape. Low CC values below 0.70 aligned with a tight velocity couplet is a strong indicator of an ongoing tornado (Ryzkhov et. al 2005). A concentrated area of CC values below 0.30 were co-located with the velocity couplet as the storm moved into downtown, suggesting a strong tornado was impacting the city at 12:41 a.m. [Figure 7].
Figure 6: Radar Reflectivity (Left) and Velocity (Right) from the National Weather Service Nashville (KOHX) at 12:41 a.m. on 03 March 2020

Figure 7: Correlation Coefficient Values at 12:41 a.m. from KOHX
As the tornado exited downtown Nashville, one of the teams from UAH SWIRLL launched a weather balloon sounding ten miles south of the center track in the city of Brentwood at 12:54 a.m [Figure 8]. This sounding collected temperature, dew point temperature, wind speed, and wind direction values as it ascended into the atmosphere behind the tornado. As the balloon rose, it interacted with the Rear Inflow Jet (RIJ) of the supercell and was accelerated toward the core of the system and the tornado. A surface temperature of 18°C and dew point temperature of 14°C present at the time of the sounding supported the warming trend that was expected to occur over the area with the lowered LCL heights observed at the 6:00 p.m. sounding from KBNA (see Figure 5). Higher CAPE values in this sounding supported an unstable atmosphere while the higher shear values supported greater longevity of the storm. The half moon shape on the hodograph (right side of Figure 8) shows veering winds with height and a classic supercell wind profile that supports rotation in the storm.

Figure 8: UAH Sounding from Brentwood, Tennessee launched at 12:54 a.m.
The supercell continued east out of Nashville toward the towns of Mount Juliet and Lebanon. At 12:54 a.m., the tornado would have its closest passage to the WSR-88D at just over eight statute kilometers to the south. A pronounced velocity couplet and co-located low CC area were still present on the radar scan as the system passed the WSR-88D [Figure 9]. The tornado remained on the ground for over sixty miles before dissipating southeast of Lebanon at 1:34 am.

Figure 9: 12:54 a.m. KOHX Radar Velocity (Left) and Correlation Coefficient (Right)
The Damage

The Nashville tornado reached Enhanced Fujita - Three (EF-3) strength (wind speeds of 136 - 165 mph) five different times during its sixty mile path of destruction through Davidson, Wilson and Smith Counties (update to the Fujita scale, Fujita 1971). Typical supercell tornadoes undergo a cycling process where the tornado temporarily weakens before strengthening again in primed environments. Over the course of the hour that the tornado was on the ground, maximum wind speeds in the core of the tornado never dropped below 90 mph, with a running average near 120 mph. The cycling process of this tornado typically alternated between the EF-1 and EF-2 scale, with winds ranging from 86 - 110 mph in an EF-1 and 111 - 135 mph in an EF-2 (National n.d.).

The NOAA Damage Assessment Toolkit provides a detailed analysis of storm surveys conducted by the National Weather Service after a severe thunderstorm event. This toolkit breaks down tornado damage by rating and provides a summary of the damage report with any associated photos. Perhaps the most beneficial feature of the toolkit is the ability to overlay archived radar data over the damage path. This allows the user to validate damage surveys with what was seen on radar at the time of the storm. For the purposes of this project, the following figures show the associated damage with the radar scan times mentioned in the previous section from the toolkit [Figures 10 and 11].
**Damage Points: Germantown**

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Figure 10: Sample Damage Report and Survey from the Associated 12:41 a.m. Radar Scan

**Damage Points: Mount Juliet**

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Figure 11: Sample Damage Report and Survey from the Associated 12:54 a.m. Radar Scan
In total, EF-3 damage was estimated to have occurred at 12:43 a.m., 12:49 a.m., 12:57 a.m., 12:59 a.m., and 1:02 a.m. The core of this project is examining the time period between 12:36 a.m. and 1:12 a.m., with a focus on the storm between 12:49 a.m. and 1:08 a.m during its closest passage to the WSR-88D, aligning with the strongest period of the tornado.

As mentioned in the introduction, a system must maintain a relative steady-state as it passes the radar for an SDD Analysis to be performed. Over 1,100 individual damage survey reports from the NOAA Damage Assessment Toolkit were hand analyzed to record the estimated maximum windspeed of the storm and scale rating between 12:49 a.m. and 1:08 a.m. Although the tornado rating oscillated between EF-2 and EF-3 during this time period, the winds maintained the relative steady-state needed. Winds typically supported a rating of a high end EF-2 or low-end EF-3, with wind variability within this rating at roughly plus or minus twenty-five miles per hour from the 111 mph threshold [Figure 12]. Note that Figure 12 is listed in Zulu Time (Z). The time conversion is covered in The Synthetic Dual-Doppler Process section.

Figure 12: Maximum Estimated Tornadic Winds between 12:49 a.m. and 01:08 a.m.
The Need for a Synthetic Dual-Doppler Analysis

Synthetic Dual-Doppler Analyses play an important role in understanding low-level wind flow and pressure perturbations in and around the core of the mesocyclone which, in this case, is the tornado itself. In the Southeastern United States, dual-Doppler analyses are not readily available due to the topography of the region and convective characteristics of thunderstorms. In these cases, a Synthetic Dual-Doppler Analysis can be run in place of that analysis. This project will loosely follow the technique presented by Klimowski and Marwitz (1992) and Murphy and Knupp (2013). SDD Analyses are still fairly uncommon and have not been extensively researched due to their strict criteria. Murphy and Knupp stated that their 2013 study would be among the first using the SDD Technique, leaving the door open for future studies to expand on their work.

Understanding the airflow around a mesocyclone is important when identifying the potential for rapid strengthening and weakening of the velocity field. This velocity change directly corresponds to the overall strength of the parent tornado. By performing the SDD Analysis, the overall kinematic and dynamic structure of the supercell can be quantified, yielding results that may improve predictive and real-time forecasting (Murphy and Knupp 2013). For this project, the low-level radar scans between 12:49 a.m. and 01:00 a.m. local time will undergo the SDD Analysis.
The Synthetic Dual-Doppler Process

The Synthetic Dual-Doppler process begins with the decontamination of the Next Generation Weather Radar (NEXRAD) Level II data, which is the same data produced from a WSR-88D radar. Level II data is available via the National Center for Environmental Information (NCEI), the Google Cloud, and Amazon Web Services. The data is free to the public and is readily available, with the ability to be instantaneously downloaded via the Google Cloud. For the purposes of this project, Level II Data was retrieved via Google instead of through NCEI or Amazon.

Acquiring Radar Data

Level II Data within the Google Cloud Storage Console is separated into four sections to simplify the process for finding a specific date and region. The data is stored into the year, month, day, and respective National Weather Service office to accurately keep track of radar scans. The call sign for the National Weather Service in Nashville is KOHX, with all available data being stored under this site. It is important to note that archived radar data is stored in Zulu (Z) time, which is also known as the Coordinated Universal Time (UTC). The city of Nashville is located in Central Time in the United States and, during early March before Daylight Savings Time, is six hours behind UTC (-6). Therefore, all radar scans needed for this analysis are stored between 0600 - 0659 and 0700 - 0759, rather than 12:00 - 12:59 a.m. and 01:00 - 01:59 a.m. [Figure 13]. Failure to adjust to UTC time will result in the collection of incorrect radar data. To better align with the times shown on the radar scans, all forthcoming times will be listed in UTC/Zulu time instead of local time.
The Level II radar data is further broken down by full volume scans that are “a series of consecutive scans, either around the horizon or in a sector, that together sweep out a volume of space” (AMS n.d.). Typical WSR-88D radars begin with a 0.5° Elevation Scan and increment up to a 19.5° scan. The smaller elevation angles are closer to the surface of the Earth than the larger angles, but vary in height as one increases distance from the radar. Full volume scans allow one to observe atmospheric continuity and vertical structure of storms to validate what is seen at the surface. The lower elevation scans provide a wealth of data for monitoring rotation and intensity of storms, as the most valuable data for surface analysis falls within the lowest two to five kilometers of the atmosphere.

Since the SDD Analysis attempts to dissect the wind flow around a mesocyclone and how the winds interact with the environment and the updraft of the storm at the surface, only the 0.5° Elevation Scan was used for this analysis. The remaining volume scans were used as reference tools to validate atmospheric continuity, but were not included in the SDD Analysis. Within these
scans, only the reflectivity (Z, in dBZ) and base velocity (V, in m s$^{-1}$) values were considered when constructing the analysis. Reflectivity is the sum of all hydrometeors (particles containing water vapor) within a given unit volume (Carey 2021). Numerous other atmospheric values are available within the Level II Data that have significant roles in other analyses, but are not necessary for an SDD Analysis.

As previously mentioned, this analysis covers the time frame between 0636Z (12:36 a.m.) to 0712Z (01:12 a.m.) with an emphasis from 0649Z to 0700Z to target the closest radar passage of the storm. Six full volume scans occurred during this time frame following the Supplemental Adaptive Intra-Volume Low-Level Scan - Three (SAILS-3) technique. SAILS-3 takes 0.5° scans more frequently than the standard radar scanning method, increasing the amount of data available that assists with the issuance of weather warnings.

**File Conversion to DORADE Sweep Files**

All twenty-four 0.5° scans between 0636Z and 0712Z were isolated and placed in a separate folder to loop each scan without a break. Once these 0.5° scans were collected, the radar decontamination process began. This process occurred within the SoloIII Radar Editing Software developed by the National Center for Environmental Research (NCAR). SoloIII allows the user to manipulate data from a WSR-88D to help improve the analysis of the storm. All WSR-88D files must be converted from GZip (.gz) file extensions to DORADE sweep files before being read into SoloIII. Each sweep file is simply just one complete sweep of a radar cycle. The remainder of the SDD Analysis process must be conducted on a Linux machine due to the requirements of the analysis softwares used. In order to convert .gz files to sweep files, one must
utilize the RadxConvert tool in the iPython Console. The following code is a sample on how to perform this conversion using the file path of the author:

```
RadxConvert -debug -dorade -outdir ./Desktop/KOHX_Capstone/20200303_Dorade -f /rhome/jhuggins/Desktop/KOHX_Capstone/radar_scan_here
```

The above command should convert all .gz files into sweep files that can be read into SoloIII. One must check the Nyquist Velocity of the sweep file to ensure the value is accurate for a WSR-88D. The Nyquist Velocity ($V_N$) is defined as the “maximum unambiguous velocity that can be detected at a given Pulse Repetition Frequency” (Integrated n.d.). A standard $V_N$ value for a National Weather Service Radar is on the order of 25-40 ms$^{-1}$. Without diving into Radar Meteorology, velocities that exceed the $V_N$ value are aliased, meaning the radar scan would appear “folded” where many values may be assigned the wrong mathematical sign. In some cases, the RadxConvert process may change the given $V_N$ and create a velocity field that does not exist. During this project, the RadxConvert process edited the $V_N$ value from 33.26 ms$^{-1}$ to 8.33 ms$^{-1}$. To avoid this change, the .gz radar files were converted to NETCDF format (.nc) before converting to sweep files. To convert to the .nc format, the iPython console was utilized with a short code written in PyART (The Python ARM Radar Toolkit) to perform the conversion:
iPython
import pyart
radar = pyart.io.read_nexrad_archive('radar_file_path_here')
net1 = pyart.io.write_cfradial(radar)

This process was repeated for all twenty-four individual radar scans. Once all the .gz files were converted to the .nc format, the aforementioned RadxConvert command was re-run, and the correct $V_N$ value was produced.

**SoloIII Decontamination Process**

Each sweep file was loaded into SoloIII for the decontamination process. Raw radar files are considered to be “noisy”, meaning that an abundance of ground clutter (non-meteorological entities) is present on the scan. In addition to ground clutter, any aliased velocity regions must be de-aliased to show the true velocity feature of the scan. One major identifier for aliased velocity is the presence of a negative value appearing in a region where the data is positive and vice versa. Positive velocity values move away from the radar while negative values move toward the radar. The orientation of these values not only provides a clue to the relative flow of the atmosphere at the time of the scan, but also highlights areas where rotation may occur.

SoloIII is set up by gates, which are small pixels that make up the radar scan. Each radar scan must be clean of ground clutter and have all velocity values de-aliased on a gate-by-gate basis before an SDD Analysis can be performed. For this research, the reflectivity range was set between -20 dBZ and 80 dBZ while the velocity range was set between -80 ms$^{-1}$ and 80 ms$^{-1}$. 
Both parameters were set with the Carbone42 color table which consists of forty-two colors in order to better differentiate closer values.

Over the course of six months, all twenty-four scans were hand edited using multiple commands within the SoloIII Editing Tool [Figure 14]. The editing tool allows the user to select a pixel or group of pixels for editing at one time, and the ability to do the edit over just one scan or all scans.

SoloIII is not an intuitive tool, nor is it user-friendly in that there is no undo button; all edits are final. In the early months of this research, over thirty attempts were made on the 0636Z scan alone due to this shortcoming of the software. Each time an edit was made and succeeded, a new copy was immediately made so that all progress would not be lost if another error occurred.
In all, eighty-seven attempts were made over the twenty-four scans before producing fully de-aliased, clutter-free scans that mitigated the loss of good data.

Five main editing tools were used in cleaning up the radar data: Despeckle, Forced Unfolding (for Velocity), Unconditional Delete (of both parameters), Set Bad Flags, and Assert Bad Flags. The Despeckle tool defines a speckle value and any gates with a smaller value surrounding the speckle are deleted. This is most useful in general clutter removal. The Forced Unfolding tool allows the user to edit the velocity values around the Nyquist Velocity value (recall the $V_N$ is 33.26 ms$^{-1}$), which unfolds the velocity back to the correct sign. This tool is most useful around the mesocyclone where the positive and negative values appear to wrap around each other and often exceed the $V_N$ value. The gates around the center of circulation must be unfolded one at a time to maximize the accuracy of the gate value and reveal the circulation core. Figure 15 shows a zoomed-in region of the mesocyclone before and after the velocity was de-aliased at 0700Z.

Figure 15: Before and after Velocity De-Aliasing at the 0700Z 0.5° Scan
The Unconditional Delete tool erases all data over a given location as if there never was any data present. This tool was used sparingly so as to not delete any good data like clear air returns. Outlying precipitation regions not directly associated with the supercell were deleted to further clean up each radar scan. The final tools heavily utilized in this project were the Set and Assert Bad Flags parameters. These tools were more readily used than Unconditional Delete as data would only be erased if it was considered to be “bad” by the user. An example of this was to Set Bad Flags for any reflectivity value below 0.0 dBZ. Reflectivity below this level is often considered bad data as it falls below the value threshold for precipitation (Knupp n.d.). By setting a bad flag for reflectivity below 0.0 dBZ, and then asserting the flag, all reflectivity gates with a value below 0.0 were deleted (just as with the Unconditional Delete tool). For this project, the Set/Assert Bad Flags tool was always used before the Unconditional Delete tool to ensure all good data had remained in the scan. Recall that SoloIII does not allow the user to “undo” an operation once it has been completed (CSU n.d.).

This process of trial-and-error was repeated over all twenty-four scans to fully decontaminate the data and make it more easily readable for the SDD Analysis. Scans before 0649Z and after 0700Z were used for verifying the atmospheric environment and were not directly involved in the SDD Analysis. Figures 16 - 19 show a before and after the decontamination of reflectivity and velocity for 0649Z, 0654Z, 0655Z, and 0700Z at the 0.5° Elevation Scan angle that were subsequently used in the analysis.
Figure 16: Before and After Data Decontamination of the Reflectivity (Top Panels) and Velocity (Bottom Panels) for the 0649Z 0.5° Elevation Scan
Figure 17: Before and After Data Decontamination of the Reflectivity (Top Panels) and Velocity (Bottom Panels) for the 0654Z 0.5° Elevation Scan
Figure 18: Before and After Data Decontamination of Reflectivity (Top Panels) and Velocity (Bottom Panels) for the 0655Z 0.5° Elevation Scan
Figure 19: Before and After Data Decontamination of Reflectivity (Top Panels) and Velocity (Bottom Panels) for the 0700Z 0.5° Elevation Scan
Conversion of Files to CFRadial and Data Gridding

Once all radar scans had been edited and cleaned of bad data, the scans were converted from the sweep files back to the .nc (cfradial) files to be gridded. Converting scans to a grid maps the data onto a Cartesian Coordinate System, rather than the Polar Coordinate System used in sweep files. Past SDD Analyses utilized the REORDER Software from NCAR to transform the radar data to the Cartesian grid. The age of REORDER and lack of recent updates left it unusable on the linux machine, leaving all data to be gridded using PyART.

Due to the nature of the data, there are errors that occur if one uses RadxConvert to convert the data back to a .nc format and then attempts to grid the data. After a month of troubleshooting with Dr. Sarah Stough of the Earth System Science Center (ESSC) at UAH, it was found that this method causes the files to store a radar latitude, longitude, and altitude for each of the fields in each scan. Therefore, each radar scan is associated with 720 location variables which causes the gridding process to fail when it attempts to read the data in as a time variable. To avoid this issue, a simple set of code was added when gridding the data to ensure the process was done correctly.

The following code describes the sequence of steps used to grid the cleaned-up radar data. This process was completed twenty-four times (once per scan) since each radar scan needed to be kept separate. Each indented line represents a new line of code:
RadxConvert -debug -cfradial -f -swp -outdir
./nas/rhome/jhuggins/Desktop/KOHX_Capstone/20200303_05Scans/20200303_cfradial

iPython

import pyart
import numpy as np
radar = pyart.io.read_cfradial('cfrad.filename.nc')
radar.latitude['data'] = np.array([radar.latitude['data'][0]])
radar.longitude['data'] = np.array([radar.longitude['data'][0]])
radar.altitude['data'] = np.array([radar.altitude['data'][0]])
grid1 = pyart.map.grid_from_radars(radar, grid_shape = (13, 241, 241), grid_limits = ((0, 6000), (-123000.0, 123000.0), (-123000.0, 123000.0), weighting_function = 'Barnes2')
time_one = pyart.io.write_grid('/nas/rhome/jhuggins/Desktop/KOHX_Capstone/20200303_05Scans/filename.nc', grid1, format = 'NETCDF4')

By denoting which latitude, longitude, and altitude the gridding process should be reading, the time and location variable returned to a value of “1” which satisfied the requirements for the gridding. The statement ‘read_cfradial’ produced a radar object that can be read in by the grid. During the gridding, the grid shape, grid limit, and weighting function was provided in order for the code to run. The grid shape has units of kilometers and is divided into three dimensions in the order of (z, x, y), where the z-dimension represents the height in the atmosphere, the x-dimension represents the East-West extent of the map, and the y-dimension represents the North-South extent. The grid limits have units of meters and are used to more tightly define the range at which the data should be gridded. Similar to the grid shape, the grid limits are divided into three dimensions in the (z, x, y) order. The grid limits for this project have a compass reach of 123 kilometers and a vertical depth of 6 kilometers. The gridding process
produced a Grid object in Cartesian coordinates that was converted back to a .nc file. These files were then converted to a .ced format that is supposedly readable by the analysis software.

**Starting the CEDRIC Software to Complete the SDD Analysis**

To finish the SDD Analysis, the user read the gridded data into the CEDRIC software, the Custom Editing and Display of Reduced Information in Cartesian space. CEDRIC allows the user to interpolate radar wind data (velocity) within a defined spatial range from a WSR-88D. The aforementioned gridding process finalized the data into three dimensions, with the x-dimension becoming $U$, the y-dimension becoming $V$ and the z-dimension becoming $W$. Through background applications and mathematical equations, CEDRIC can allow an “over-determined or least squares solution for $(U, V)$ in terms of measured radial velocities, associated radar geometries, and an unknown vertical velocity distribution…[and can] compute horizontal or coplane convergence, the negative of divergence of the horizontal winds from the solutions” (Miller and Fredrick 1998, 2009).

Recall that one of the main criteria for an SDD Analysis is a sufficiently large SMV that yields a large enough angle of geometric difference between two timestamps. Given an average SMV of 27 ms$^{-1}$ for this storm, the time periods of 0649Z - 0654Z and 0656Z - 0700Z were analyzed for this SDD Analysis. The speed of the system produced a geometric angle difference of 34° for the first time period and an angle difference of 44° for the second [Figures 20 and 21].
Figure 20: Geometric Angle Difference between 0649Z (Left) and 0654Z (Right) via GR2Analyst at the 0.5° Elevation Angle

Figure 21: Geometric Angle Difference between 0656Z (Left) to 0700Z (Right) via GR2Analyst at the 0.5° Elevation Angle
The SDD process yields a geometric set-up in which the original radar position is translated to maximize the reflectivity and velocity fields (e.g. where the incident angle is maximized). The SMV of 27 ms\(^{-1}\) mentioned in the previous paragraph was used to determine the translation vector between the two time periods, 0649Z-0654Z and 0656Z-0700Z, thus defining the coordinates for the translated radar. A simple calculation was used to determine the location of the translated radar (R\(_2\)):

\[ R_2 = c \Delta t_s \]

where \(c\) is the storm speed (SMV, 27 ms\(^{-1}\)) and \(\Delta t_s\) is the time between radar scans in seconds. The location of this synthetic radar is placed in the direction from which the storm is moving before it reaches the WSR-88D (in this case toward the west), and in the opposite direction after radar passage. The Nashville radar is located at (36\(^\circ\) 14’ 50”, -86\(^\circ\) 33’ 45”). Therefore, this calculation produced a second radar location 8.1 km to the west of the KOHX WSR-88D at (36\(^\circ\) 14’ 50”, -86\(^\circ\) 39’ 05”) for 0649Z and 0654Z. Subsequently, the next scans after the storm passed the radar placed the second location at 8.1 km to the east of the WSR-88D at (36\(^\circ\) 14’ 50”, -86\(^\circ\) 28’ 19”). Figure 22 shows a sample geometric set up from Lhermitte and Miller (1970).
Horizontal wind flow is relatively simple to determine based on the speed and direction of the SMV during the timespan of the analysis (Ray et al. 1985). For this project, the averaged SMV was used as the baseline for all wind retrievals. The vertical wind flow is more complicated to obtain. There are three main methods for determining vertical velocities within CEDRIC, the “upward integration using a surface boundary condition…[a] downward integration using a storm-top boundary conditions…or a variational scheme using both surface and storm-top boundary conditions” (Murphy 2013; O’Brien 1970). This project utilized the variational method to infer vertical velocities in an attempt to mitigate sources of error. Significant errors may arise in the upward integration method as radar scans do not start from ground level and increase in starting elevation for storms that are farther away due to the curvature of the Earth. Therefore, any accrued errors between the upward and downward
integration processes can be redistributed with the variational method to limit overall errors (Murphy 2013).

Before the SDD Analysis can be run, the file directories and filenames were set to a distinct path that simplifies the ‘read’ process. From there, a Fortran Logical Unit Number (LUN) was also supplied. One file path is for the “input file” with a .inp extension. This file contains all of the steps to run within the CEDRIC commands. In this file, CEDRIC was set to read in the volume data (including the assigned LUN), change the variable names, write the volume data, perform a Convergence of the $U$ and $V$ Vectors, and Integrate the interpolated data in the $W$ direction, manipulate the location of the second radar, among others [Figure 23].

![Sample CEDRIC Input File](image)

Figure 23: Sample CEDRIC Input File
Numerous parameters and values were supplied in the input file in order for the SDD to run. By using this input file, CEDRIC is able to run an SDD Analysis when the coordinates for the synthetic radar are provided. A listing of these values can be found in the CEDRIC User Guide (Miller and Fredrick 1998, 2009). In addition to the .inp file, CEDRIC requires the gridded data files to be imported in a .ced format that is typically an output of the REORDER software. The gridded files from PyART (since REORDER was unusable) were attempted in CEDRIC to see if the software would run. Although these files were in the .ced format, CEDRIC could not read in the files and therefore, the gridded files could not be used.

Second Attempt at Gridding the Radar Data

PyART originally was the best option to grid the data into Cartesian Coordinates to avoid the coplane stage without having REORDER. The coplane stage often creates discrepancies between the latitudinal and longitudinal range of the radar that can alter the viewing profile. After spending over a month manipulating PyART to produce the gridded data, the files would not load into CEDRIC. Thus, a different gridding method was used.

Part of the development of LROSE (Lidar Radar Open Software Environment), which includes CEDRIC and SoloIII, included multiple ways to grid radar data. The Radx2Grid tool converts radar data into a Cartesian Coordinate System in the orientation (z, y, x) through a series of user-inputted commands into a parameter file. Many of the parameters were kept congruent to or similar to what was defined in the PyART gridding process. However, a few notable changes were made that would satisfy the CEDRIC requirements. The most important of these changes was directly setting the output format of the conversion to a “CEDRIC” format. This
automatically converted all output files to the .ced format. Table 1 shows a brief list of the commands used when re-gridding the data.

<table>
<thead>
<tr>
<th>Command</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>debug = DEBUG_NORM</td>
<td>Turns on debugging function</td>
</tr>
<tr>
<td>input_dir</td>
<td>Input Directory for Searching for Files</td>
</tr>
<tr>
<td>mode = FILELIST</td>
<td>Moves through the list of files on the command line</td>
</tr>
<tr>
<td>output_dir</td>
<td>Output Directory for Writing Files</td>
</tr>
<tr>
<td>output_format</td>
<td>Sets the Output Format</td>
</tr>
<tr>
<td>interp_mode = INTERP_MODE_CART</td>
<td>Sets the Interpolation Mode to Cartesian Coordinates</td>
</tr>
<tr>
<td>grid_z_geom</td>
<td>Specifies the regular vertical grid levels</td>
</tr>
<tr>
<td>grid_xy_geom</td>
<td>Specifies the grid parameters in x and y</td>
</tr>
<tr>
<td>grid_projection = PROJ_FLAT</td>
<td>Projection details for the Cartesian Grid</td>
</tr>
<tr>
<td>override_beam_width</td>
<td>Option to override beam width</td>
</tr>
<tr>
<td>beam_width_deg_h = 1</td>
<td>Sets horizontal beam width to 1°</td>
</tr>
<tr>
<td>beam_width_deg_v = 1</td>
<td>Sets vertical beam width to 1°</td>
</tr>
</tbody>
</table>

Table 1: Brief Overview of Radx2Grid Commands

After resetting each of the Radx2Grid commands within the parameter file, the following code was re-run to produce gridded files in the .ced format to be loaded into CEDRIC:

```
Radx2Grid -params $PWD/NewGrid.params -f /input/file/path
```
The files produced from the Radx2Grid tool were readable by CEDRIC and were inputted following the earlier processes mentioned in this report.

**Second Attempt at CEDRIC**

Once all the file paths were set for the gridded data and input files, the SDD Analysis was attempted for 0649Z, 0654Z, 0656Z, and 0700Z. Numerous problems were encountered while trying to supply the coordinates of the second synthetic radar. The main issue came from trying to manipulate the ID values for the new location. Several attempts were run with a test input file to produce the edited ID values that could then be imported into the main input file. None of the attempts were successful in changing the ID values so the software could not perform the SDD Analysis. Due to time constraints, the full SDD Analysis could not be completed prior to the deadline of this project. Future work will solve the ID issue and run CEDRIC.

Once CEDRIC runs, the analysis will produce horizontal wind fields in the \( U \) and \( V \) directions and an interpolated wind field in the \( W \) (vertical) direction. CEDRIC runs a plethora of meteorological equations in the background in order to produce these results. A brief synopsis of these equations is shown below:

Radial Velocity in Terms of \((U, V)\):

\[
\frac{\hat{v}_r}{r} t + \Delta t = \hat{u} \left( x - x_0 + \frac{u \Delta t}{r} \right) + \hat{v} \left( y - y_0 + \frac{v \Delta t}{r} \right) + \hat{w} \left( z - z_0 \frac{z}{r} \right) t
\]
For a Radar at \((x_0, y_0, z_0)\) with Slant Range:

\[
r = \left[ (x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 \right]^{1/2}
\]

Solving for Vertical Motion using the FUNCTION tool on CEDRIC for simplicity

Mass Continuity Equation:

\[
\frac{\partial (\rho w)}{\partial z} + \frac{\partial (\rho u)}{\partial z} + \frac{\partial (\rho v)}{\partial y} = 0
\]

Such that:

\[
\int_{z_k}^{z_{k+1}} \frac{\partial (\rho w)}{\partial z} dz = -\int_{z_k}^{z_{k+1}} p \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) dz
\]

Or, in finite difference form (an equivalent form):

\[
(\rho w)_c = (\rho w)_p - \delta\Delta z \left[ p \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) \right]_{p-c}
\]

where:

\[
\delta = \{+1 \text{ for upward integration, } -1 \text{ for downward integration}\}
\]

The overbar in the finite difference formula represents an overall average of the divergence values that were found in the convergence computation for \((U, V)\) [see CONVERGECONV on Figure 23]. Mathematically speaking, the “negative divergence” mentioned in Miller and Fredrick (1998, 2009) is the convergence value, so this equation essentially flips the sign of the convergence value found in the SDD process. There are other
processes to calculate the integrated vertical velocity, however the text lists that those steps are more mathematically rigorous than the equations shown above, but still yield similar results (Miller and Fredrick 1998, 2009).

Once the ID values are fixed, CEDRIC will be able to fully dissect the wind field around the mesocyclone and identify how the storm interacted with the environment via the SDD method. Should the input file not change the ID values, the Radx2Grid tool will be utilized again to override the radar location to produce a second .ced file. From there, both files will be read into CEDRIC simultaneously to trick the software into thinking there was a second radar. This will allow CEDRIC to produce the three-dimensional wind field that encompasses a Synthetic Dual-Doppler Analysis. Without fixing the ID values, CEDRIC would run a Single-Doppler Analysis, an important analysis but one that is limited in scope.
Data and Results

Although the SDD Analysis attempts in CEDRIC have not yet been successful, the newly gridded radar data was able to be read in by the software. By manipulating the parameters to a vertical grid spacing of 500 meters starting at 250 meters above ground level, the software did produce the maximum and minimum reflectivity and velocity values at each of the lowest elevation levels seen in the 0.5° scan [Figure 24].

These results indicate that the software can be run, and that once the radar location issues are satisfied, the SDD Analysis should be able to successfully run.

---

Figure 24 : Sample .log File Produced by CEDRIC
Once the SDD Analysis is performed, multi-dimensional wind profiles will be produced at several points during the closest passage of the storm to the radar. By using the first and last 0.5° scan of a set volume time associated with a large SMV, the behavior and evolution of winds will become more clear than in a standard radar view. The main goal of these results is to reconstruct the vertical wind profiles of the tornado from the surface to see how the updraft interacted with a high shear, low CAPE cool environment. In an ideal situation, cyclonic wind circulation will be seen at the lowest levels with respect to the mesocyclone. The main question still is how the vertical component of the winds shifts with height. These vertical perturbations can provide clues to the nature of tornadoes and how environmental interaction can affect their path and strength.

With few SDD Analyses being performed prior to this study, information on these softwares is limited and creates a time-consuming process that dives deep into Radar Meteorology. Therefore, it is difficult to pinpoint exactly what can be expected from these results. Until the analysis is performed, the true vertical perturbation of the winds will remain a mystery.
Error Analysis and Future Work

Numerous sources of errors are possible when running an SDD Analysis. The ability for the wind field to be resolved relies heavily on the radar decontamination process in SoloIII. If the velocity fields are not fully unfolded and dealiased, wind perturbations around the mesocyclone may point in incorrect directions. Another main error source could come from the placement of the second synthetic radar. Since this radar does not physically exist, the geometric set-up had to be manipulated using the SMV and volume scan times. Since an average SMV was used for this analysis, the results may be skewed if the actual SMV was faster or slower [therefore changing the location of the second radar]. A more complete analysis of potential SDD errors can be found in Murphy (2013).

The SDD Analysis will be run four different times to fully capture both the start and end point of the storm once the 30° angle difference was met. Each time CEDRIC is run, the software produces a .log file that compiles the results of the analysis as seen in Figure 24. For the purposes of this analysis, the grid spacing will be initially set to 1 km on a 100 km x 100 km grid. The vertical direction will stay incremented by 500 meters (0.50 km) over the lowest elevations to produce results up to 5 kilometers in height. The small vertical spacing is due to only having the 0.5° Elevation Scan being used for this analysis; therefore, only the lowest few kilometers need to be seen. The results from the SDD Analysis will then be read into a Python script to plot the vector fields as NCAR Graphics are disabled on the available CEDRIC software.
The future work on this project will encompass adjusting the viewing angle of the SDD to better refine the spatial resolution and gridding range. By manipulating the spatial resolution, longer volume scans can be analyzed for a more comprehensive look at the evolution of the system as it passed the WSR-88D. Refining the spatial resolution will take longer to run in CEDRIC but may produce more viewable results to better understand the wind field of this tornado. Furthermore, the data will be revisited in SoloIII to attempt further data decontamination, specifically for the velocity around the mesocyclone. The aforementioned results were only a trial run in the novel CEDRIC software that has not been extensively used for SDD Analyses. As knowledge of CEDRIC increases, there is hope to complete more SDD and multi-Doppler analyses on past cases to further uncover the secrets of one of Mother Nature’s most vicious phenomena.
Conclusions and Final Statements

The Nashville tornado formed in a seemingly unfavorable environment that forever changed the landscape of Central Tennessee. This high shear, low CAPE supercell produced four more tornadoes after Nashville, including a stronger tornado rated EF-4 (winds 166 mph - 200 mph) that impacted the city of Cookeville. Several key ingredients converged in just the right area to not only progress, but strengthen the storm on its eastward track.

By performing a Synthetic Dual-Doppler Analysis, there is hope that these results may one day assist in predictive and real-time forecasting to better the advanced warning system. Understanding the behavior of low-level winds around a tornado and the associated vertical wind profile may one day improve tornado prediction through the numerous upgrades to the WSR-88D.

The night of 02-03 March 2020 provided a unique opportunity to explore a research topic not heavily studied in meteorology. By providing another case for an SDD Analysis, there is hope that future research can expand on this project to better understand how a tornado interacts with the environment. In a game of man versus Mother Nature, Mother Nature is usually the victor. Staying weather aware is only a small part of keeping everyone safe, but perhaps remains the most important way to save lives in the future.
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