Taking Action: A Case Study Analyzing the Deficiencies and Potential Opportunities for Improvement in the Severe Weather Warning System

Carson Meredith

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TAKING ACTION: A CASE STUDY ANALYZING THE DEFICIENCIES AND
POTENTIAL OPPORTUNITIES FOR IMPROVEMENT IN THE SEVERE WEATHER
WARNING SYSTEM

A Capstone Project Presented in Partial Fulfillment
of the Requirements for the Degree Bachelor of Science
with Honors College Graduate Distinction
at Western Kentucky University

By
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April 2019

*****

CE/T Committee:
Professor Joshua Durkee, Advisor
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ABSTRACT

The United States is one of the most prone areas in the world to experience severe weather. A warning system operated by the National Weather Service alerts the public of the dangers of severe weather. The purpose of this project is to analyze the effectiveness of the National Weather Service warning system across Kentucky and Tennessee. A case study is presented analyzing six severe weather events in areas warned by the National Weather Service offices in Louisville, Kentucky and Nashville, Tennessee in 2018. Factors reviewed include effectiveness in issuing timely warnings, verification (i.e., whether or not severe weather actually occurred), and which office performed better in issuing warnings, among others. Results from these events are then used to analyze the effectiveness of these warnings and raise questions about any deficiencies that may have been identified in the warning process in this case study. While most warnings with these six events were effective in protecting the public, there were still noticeable errors or missteps with the warning process in each of these events that should be addressed in order to improve the warning process in the future. These errors and missteps are summarized as a series of questions at the end of each event analyzed in this case study, with big picture questions serving as the basis for future research in improving the severe weather warning process.
Dedicated to my family and my friends.
ACKNOWLEDGEMENTS

I want to first thank my faculty advisor, Dr. Josh Durkee, for his support through the CE/T process and for his thoughtful contributions and insightful suggestions with this project. I also wish to thank Dr. Durkee for the opportunities he has given me during my time here at WKU through Storm Chase and White Squirrel Weather. The students of the meteorology program are forever grateful for his tireless efforts in growing the WKU meteorology program and for his constant support and drive for all of us to succeed. I also want to thank Dr. Greg Goodrich for his continued support during my time here at WKU as well.

In addition, I want to thank my friends in the meteorology program and beyond for their constant emotional support through this process and throughout my four years in the meteorology program. In a major as daunting as meteorology, it is hard to succeed without the support from your fellow peers. I am grateful not only to call these people my colleagues, but also my friends.

Last but not least, I want to give a special thanks to my family for their constant love, faith, and support in me these last four years and on this project. Without their encouragement to carry on and push forward, I honestly cannot say for certain that this project would have come to fruition. I am forever grateful for their desire for me to succeed and for their willingness to sacrifice anything to ensure that I would be able to achieve my dream of becoming a meteorologist.
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CHAPTER ONE

AN INTRODUCTION TO THE WARNING PROCESS

The National Weather Service (NWS) and County Warning Areas (CWA)

The National Weather Service (NWS) is an agency within the United States Department of Commerce. The NWS is responsible for providing “weather, water, and climate forecasts and warnings for the United States, its territories, adjacent waters and ocean areas, for the protection of life and property and the enhancement of the national economy” (NWS, 2019). The NWS provides services that include forecasts for local areas, warnings, Impact-Based Decision Support Services (IDSS), and education about the weather and the services they provide. In addition to protecting life and property and enhancing the national economy, NWS endeavors to create a society that is prepared to respond to weather, water, and climates (NWS, 2019). NWS forecasts and warnings are provided to decision makers at all levels of government (local, state, federal) in order to protect life and property.

The NWS national headquarters is located in Silver Spring, Maryland, a suburb of Washington, D.C. National headquarters is responsible for the management of the entire NWS. The NWS is then split into six regional headquarters: Eastern, Southern, Central, Western, Alaska, and Pacific (see Figure 1.1). These regions manage the operational and scientific programs across the region. These programs include observing networks,
weather services, forecasting, hydrology, and climatology (NWS, 2019). Within these six regions are the 122 NWS Warning Forecast Offices (WFOs) that are responsible for issuing advisories, warnings, and forecasts to the public. These products issued by WFOs are also distributed to local media outlets, emergency management agencies, and members of the aviation community (NWS, 2019). WFOs are manned by forecasters 24 hours a day, 7 days a week. Forecasters produce digital content, issue watches, warnings, advisories, aviation forecasts, and river forecasts, all with the goal of protecting the public from weather hazards.

![National Weather Service Regions](image)

Figure 1.1: The six regional headquarters of the National Weather Service (NWS). (Courtesy NWS)

Each of the 122 NWS Weather Forecast Offices nationwide preside over a set County Warning Area (CWA). These NWS offices are responsible for issuing severe weather warnings and forecasts for counties that fall in their CWA. There are no set
criteria that defines how large and/or how many counties are within a CWA, meaning some CWAs are larger than others across the United States. Many CWAs boundaries cover multiple states and multiple time zones as well. Figure 1.2 shows a national map of all CWA boundaries and the corresponding NWS offices responsible for providing weather information to those areas.

Figure 1.2: A map of the 122 National Weather Service Weather Forecast Office County Warning Areas (CWAs). (Courtesy NWS)

In this case study, the focus will be on two NWS Weather Forecast Offices: Louisville, Kentucky and Nashville, Tennessee. These two offices are chosen primarily for their relevance to our region as the Louisville office is responsible for weather information in Bowling Green and the Nashville office is in close geographic proximity.
to Bowling Green. In addition, this case study will also focus on some of my personal experiences as a Student Volunteer at both of these offices during the 2018 calendar year. Each of these offices and their County Warning Areas are quite different, providing two distinct perspectives of how NWS offices execute the warning process. NWS Louisville covers 59 total counties: 49 counties in Kentucky and 10 counties in southern Indiana. Louisville’s CWA includes the three largest cities in Kentucky: Louisville, Lexington, and Bowling Green, as well as counties in both the Eastern and Central time zones. NWS Nashville, however, covers just 38 counties, all of which are in middle Tennessee and in the Central time zone. In addition to Nashville, the CWA also includes Murfreesboro, Tennessee. The outlines of each of these CWA boundaries can be seen below in Figure 1.3.

Figure 1.3: Outlines of NWS Louisville (white) and NWS Nashville (gray) County Warning Areas (CWAs). (Courtesy NWS Louisville and NWS Nashville)
**Key Terms and Definitions**

In order to attain a full grasp of the effectiveness of the warning process over the course of this case study, it is important to have a basic understanding of some of the terms used in the analysis. These terms are commonly used in the meteorological field, but are uncommon in day-to-day dialogue. These terms primarily relate to key components in verifying and analyzing the effectiveness of severe weather warnings, as well as radar products that are used in making critical warning decisions during times of severe weather.

The accuracy of the severe weather warning system can be quantitatively analyzed by using several metrics. With any severe weather event, it is important for NWS meteorologists to provide ample warning time to the public that severe weather conditions are approaching a given location. The *lead time* metric is the amount of time a warning was issued ahead of severe weather phenomena that resulted in the warning officially occurring. For example, if a Tornado Warning is issued for an area at 4:00 PM, and a tornado does not officially touch down in the warning area until 4:10 PM, then it is determined that the warning provided a 10-minute lead time before a tornado touched down. Depending on the shape and structure of the severe storms in question, the lead time on Tornado Warnings can vary. Some severe storms, most notably supercells, typically provide the greatest amount of lead time in Tornado Warnings. Supercells refer to an isolated single-celled storm that consists of a rotating updraft that can last for up to several hours depending on the environment in place. Supercells are largely considered...
the most dangerous type of storm mode, and the primary contributor to strong and violent tornadoes on record. Strong and violent tornadoes are rated between EF-2 and EF-5 on the Enhanced Fujita Scale. Radar imagery depicting a ‘classic’ supercell can be seen below in Figure 1.4.

![Radar Imagery of a ‘Classic’ Supercell](image)

Figure 1.4: Radar imagery of a ‘classic’ supercell. Most violent tornadoes that occur develop from supercells with similar structure. (Courtesy Prociv)

Some Tornado Warnings can also have zero or negative lead time. Negative lead time represents a Tornado Warning issued after the initial report or impact of a tornado in association with a storm. A zero lead time Tornado Warning means the warning was issued at the same time a tornado was touching down in the warned area. These types of Tornado Warnings are more common with tornadic circulations along a line of severe thunderstorms. These circulations do not possess the updraft intensity seen in supercells that are strong enough to stay present for hours at a time. Rather, the circulations ‘pulse
up’ at random times as the line progresses through an area for a brief period before weakening once more. This pattern is often cyclical over the life time of a line of severe storms. Due to the random nature of these rotations pulsing up and weakening soon after, it is very difficult to provide sufficient lead time in issuing Tornado Warnings associated with these circulations. Thus, the lead time associated with the smaller, less damaging tornadic circulations along a line of severe storms is often much lower compared to Tornado Warnings issued for supercellular storms.

Following severe weather events, NWS meteorologists conduct storm surveys in their coverage area to determine whether or not severe weather phenomena occurred. When it is determined that severe weather did not occur in an area that a severe weather warning was issued, the warning is then considered a false alarm and is not verified. The rate at which false alarm warnings are issued by a local NWS office is considered its False Alarm Rate (FAR). Like the decrease in warning lead time associated with embedded tornadic circulations along a line of severe storms, the FAR increases in these storm mode scenarios. In other words, as lead time decreases, the accuracy of warnings decreases, causing false alarms to increase, thus increasing the FAR. By contrast, if severe weather phenomena occurred in the area at the time a warning was in effect, the warning is then considered verified. If severe weather phenomena occurred in an area where a warning was not in effect, it is considered a missed warning. For perspective, during the 2018 calendar year, NWS Louisville had a Tornado Warning FAR of 0.82 while NWS Nashville had a Tornado Warning FAR of 0.69. This means that 82 percent
of Tornado Warnings issued by NWS Louisville did not involve an actual tornado touchdown or the tornado occurred before the warning had been issued. Similarly, 69 percent of Tornado Warnings issued by NWS Nashville also met this same criteria to be considered a false alarm.

When analyzing a severe weather event as it happens and after it occurs, it is critical to have an understanding of the radar products being used. As a severe weather event unfolds, forecasters rely heavily on numerous radar products to assist in decision-making purposes during the warning process. While evidence via photos or videos on social media may be useful in telling the story after the event or in some cases as the event is occurring, the decision to issue severe weather warnings hinges largely on the radar products being used by NWS forecasters and their knowledge of what each product is showing them. While there are many radar products that can be used, this case study will focus largely on five specific radar products that were used in the warning process for each of these events. Below is a bulleted list of each of these products and their associated purpose (from Durkee, 2019).

- **Base Reflectivity (BR)**-the classic radar imagery commonly used in broadcast television and online services. This measures the intensity of precipitation and its movement and can determine the structure of storms as well as any boundaries that could contribute to storm development (i.e., cold front, warm front, etc.)

- **Base Velocity (BV)**-product used to estimate wind speeds and direction, as well as areas of wind shear (crucial in tornado development), locating boundaries, and
identifying storm structure. Wind direction is indicated by color (red means winds are moving away from the radar; green means winds are moving towards the radar). Wind speed is indicated by the brightness of these colors.

- **Storm Relative Velocity (SRV)** - similar principle to Base Velocity, but instead can be used to examine the winds within a single thunderstorm. Subtracting the storm motion from the velocity can aid in determining areas of rotation that might otherwise be obstructed. This often provides a higher-resolution velocity product.

- **Correlation Coefficient (CC)** - measures the uniformity of objects being observed by radar. A low correlation indicates objects being observed by radar are less uniform. Meteorological features typically have a CC value around one (1). Anything less than 0.8 is likely non-meteorological objects (birds, debris, etc.). In severe weather, CC can be used as evidence to suggest debris is being lofted as a result of a tornado. Lower correlations are indicated by cooler colors (blue, gray, etc.) on the CC product.

- **Normalize Rotation (NROT)** - attempts to find areas of rotation based on base velocity (BV) products. NROT values range from -5.0 to +5.0. Values above 1.0 are significant in searching for potential tornadic development. Values above 2.5 are extreme.
Communicating Severe Weather Threats

Communicating severe weather threats to the public is perhaps the greatest challenge that meteorologists have on a daily basis. The way forecasters communicate potential severe weather threats can vary widely from event to event. Some events may only appear to pose a severe threat the day of the event itself, meaning reduced opportunity to communicate a threat. As a result, there could be very little preparation time for the public. More organized severe weather events forecast on computer models consistently several days leading up to a possible event provide time for more communication of potential severe weather events and perhaps more accurate forecasting.

Regardless of how the event unfolds, there is a general severe weather forecasting ‘chain of command’ that allows for people across the United States to prepare for potential severe weather in advance of an event and to be alerted that severe weather is occurring as the event unfolds.

Several times a day, the Storm Prediction Center (SPC) in Norman, Oklahoma is responsible for issuing Convective Outlooks. These Convective Outlooks are designed as a ‘first call’ for potential severe weather in the coming days. The SPC issues these outlooks for the current day (considered the Day 1 Convective Outlook) and up to one week in advance (considered the Day 8 Convective Outlook). The specificity of these Convective Outlooks increases as the forecast gets closer to the current day. For example, the Days 4-8 Convective Outlook are grouped together and only outline areas with
percentage chances for seeing severe weather (Figure 1.5). As the forecast gets closer to the current day, the number of Convective Outlooks issued also increases (Table 1).

Table 1

<table>
<thead>
<tr>
<th></th>
<th>Day 1</th>
<th>Day 2</th>
<th>Day 3</th>
<th>Days 4-8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:00 AM</td>
<td>1:00 AM</td>
<td>2:30 AM</td>
<td>4:00 AM</td>
<td></td>
</tr>
<tr>
<td>8:00 AM</td>
<td>12:30 PM</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>11:30 AM</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>3:00 PM</td>
<td>Further</td>
<td>Further</td>
<td>Further</td>
<td></td>
</tr>
<tr>
<td>8:00 PM</td>
<td>Updates</td>
<td>Updates</td>
<td>Updates</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1.5: An example of a Day 4 Convective Outlook issued by the Storm Prediction Center in Norman, Oklahoma. (Courtesy SPC)

By the Day 3 Convective Outlook, however, the percentage chances for severe weather then correspond to a specific label that indicates the potential for severe weather.
The SPC uses five of these labels to indicate the risk for potential severe weather: Marginal, Slight, Enhanced, Moderate, High. These can also be correlated with numbers on a 1 to 5 scale (i.e., Marginal = Level 1, Slight = Level 2, etc.). The higher the label and the corresponding number, the greater the risk for severe weather. A graphic explaining the meteorological differences between each of these five severe weather risk levels can be seen in Figure 1.6.

### Understanding Severe Thunderstorm Risk Categories

<table>
<thead>
<tr>
<th>THUNDERSTORMS (no label)</th>
<th>1 - MARGINAL (MRGL)</th>
<th>2 - SLIGHT (SLGT)</th>
<th>3 - ENHANCED (ENH)</th>
<th>4 - MODERATE (MDT)</th>
<th>5 - HIGH (HIGH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No severe* thunderstorms expected</td>
<td>Isolated severe thunderstorms possible</td>
<td>Scattered severe storms possible</td>
<td>Numerous severe storms possible</td>
<td>Widespread severe storms likely</td>
<td>Widespread severe storms expected</td>
</tr>
<tr>
<td>Lightning/flooding threats exist with all thunderstorms</td>
<td>Limited in duration and/or coverage and/or intensity</td>
<td>Short-lived and/or not widespread, isolated intense storms possible</td>
<td>More persistent and/or widespread, a few intense</td>
<td>Long-lived, widespread and intense</td>
<td>Long-lived, very widespread and particularly intense</td>
</tr>
</tbody>
</table>

* NWS defines a severe thunderstorm as measured wind gusts to at least 58 mph, and/or hail to at least one inch in diameter, and/or a tornado. All thunderstorm categories imply lightning and the potential for flooding. Categories are also tied to the probability of a severe weather event within 25 miles of your location.

Figure 1.6: An informational graphic describing the five labels of severe weather outlooks issued by the Storm Prediction Center. (Courtesy SPC).

As the forecasts get closer to the current day, the confidence in the severe weather forecast increase. Because of this, additional percentage risks are introduced to include the risk for tornadoes, damaging winds, and severe hail for the current day outlook (Day 1). The remaining days only include general percentages for some sort of severe weather to occur, but do not go into specific modes. The amount of outlooks issued by the SPC...
also increase as the event gets closer. Outlooks are only issued once a day for Days 3-8, twice a day for Day 2, and four times a day for the current day (Day 1).

As a severe weather event begins to unfold, severe weather alerts will be issued in advance of the event and as the event is actually occurring. In the hours leading up to the beginning of possible severe weather, the SPC issues severe weather watches if there is reason to believe severe weather is possible for certain areas of the country. In terms of severe weather, the two watches that are issued are Severe Thunderstorm Watches and Tornado Watches. If a substantial tornado threat is present, the SPC will typically issue a Tornado Watch as a precautionary measure. However, if the tornado threat is lower or does not appear to be widespread, a Severe Thunderstorm Watch will be issued. Watches cover much larger areas compared to warnings. Watches typically include multiple states, and last for several hours, if not longer. Watches are designed to alert the public that there is a potential for severe weather and advises the public to prepare for the possibility of severe weather and to stay alert for any warnings that may be issued as the event unfolds. A good way to remember the meaning of severe weather watches is they serve as a “heads up” for possible severe weather. However, it is important to note that the issuance of severe weather watches does not directly correlate with actual severe weather occurring. Severe weather may still happen even without a watch being issued. Conversely, a watch may be issued, but no severe weather may take place. Watches are only designed as a guide for areas where potential severe weather could occur, but do not guarantee severe weather will actually take place.
During a severe weather event, control of severe weather alerts shifts to local NWS warning forecast offices. It is at the discretion of each of these offices to issue warnings for their CWAs if they feel that there is an immediate danger to the public. These warnings are designed to alert the public of these dangers and urges with the public to seek substantial shelter. The SPC has no role in issuing these warnings. However, like the SPC, local NWS offices have the same two severe weather categories: Severe Thunderstorm and Tornado. Local NWS offices issue Severe Thunderstorm Warnings for storms capable of producing at minimum 58 miles per hour (MPH) wind speeds and/or one-inch diameter hail (equivalent to quarter size). A common misconception with the issuance of Severe Thunderstorm Warnings is that lightning in a storm indicates severity. By definition, all thunderstorms have lightning. Therefore, if lightning was a criterion for severity, one could feasibly argue that every thunderstorm is severe. All thunderstorms have lightning, but not every thunderstorm is severe.

Tornado Warnings are issued by local NWS offices when the threat for a tornado is imminent. A tornado may not be on the ground, but radar data may suggest that a tornado may develop at any moment. These are commonly referred to in the text of Tornado Warnings as “Radar Indicated” tornadoes. Tornado Warnings can also be issued when a tornado has been spotted on the ground by a member of the public, local law enforcement, or trained storm spotters. In recent years, NWS forecasters have had the option of a ‘middle ground’ between Severe Thunderstorm and Tornado Warnings by issuing a Severe Thunderstorm Warning with a “Tornado: Possible” tag at the end of the
warning message. This tag indicates that while a storm is not producing enough evidence to issue a full Tornado Warning, data indicates a possible tornado even with no Tornado Warning in effect. Regardless of the type of warning that is in effect, these warnings cover a much smaller geographic area than the watches issued by the SPC. Just as a watch acts as a “heads up” for *everybody* in an area for possible severe weather, a warning serves as a “take action” for *a select few* in a smaller area where severe weather is imminent or actually occurring. Warnings typically only span portions of a few counties at a time. Warnings also do not last as long as watches, typically only in effect 30 minutes to one hour. Warning duration depends on the strength of the storm in question, the storm’s motion, and the threats associated with the storm. NWS offices decide when to issue these warnings and when to allow them to expire or to be terminated early if the threat has diminished. NWS offices also end the watches issued by the SPC as the severe weather event begins to wind down.

**The Psychological Impact of the Warning Process**

As meteorologists, it is important to remember that the ultimate goal of the severe weather warning process is to protect the lives and property of the people they serve. With this in mind, it is imperative that meteorologists have a warning process in place that the public will not only use to protect themselves during a severe weather event, but also that they have a real understanding of the severe weather threat that may occur and the damage to life and property that could take place. What makes the warning process
challenging is that it is a shared responsibility. After the meteorologists analyzing the event have done their part in issuing these warnings, it is then up to the public to recognize and accept these warning messages and act upon them. Past research on the subject of severe weather warnings and their impact on the public have suggested that there are still deficiencies in the way the public interprets severe weather warnings. One publication suggests that the wording or tone of the warning can actually have an effect on how the public interprets the warning’s credibility (Perreault et al. 2014). Unverified warnings or false alarms can also further fuel the credibility debate, with a potentially devastating effect on those in the public who ignore warnings issued whenever an actual life-threatening emergency is occurring.

False alarm warnings and the FAR are perhaps the most critical metric used to assess the effectiveness of the warning process as it relates to public reaction during severe weather events. Prior to the current severe weather warning technology in place across much of the country, National Oceanic and Atmospheric Administration (NOAA) weather radios were the primary source for receiving severe weather information from the NWS. However, prior to 1997, any time a warning was issued anywhere in the radio coverage area, the alarm would sound, even if the area the weather radio was located was not a part of the warnings. Because of this, only 10 to 25 percent of all warnings issued would even be relevant to where a weather radio was located. Much of the public became numb to the weather radio alarms and began to turn off their weather radios during severe weather events. Turning off the weather radio often meant people had no other way of
receiving severe weather warnings. This tactic is extremely dangerous at night when the weather radios could sound to wake people and allow them to take proper action for the impending severe weather threats (Coleman et al. 2011). Fortunately, the introduction of the Specific Area Message Encoding (SAME) county-specific code system in 1997 greatly reduced the amount of weather radio activations by sounding only when a particular county was placed under a warning as opposed to every county in the radio coverage area. These SAME codes and reduced weather radio activations would make these radios more popular nationwide and would help in reducing the “cry wolf” syndrome to some extent (Coleman et al. 2011).

The job of meteorologists in the warning process can only go so far before the process, and its effectiveness, is in the hands of the general public. Therefore, having effective communication with the public about severe weather warnings as well as the potential impacts associated with these warnings must be a top priority for all meteorologists. Effective communication will allow for the public to acquire a greater understanding of threatening weather and the potential impact that this threatening weather may have on their life and property. It is the responsibility of each NWS office to provide effective descriptions of the potential hazards each severe weather event poses to the public, and what precautionary actions should be taken to mitigate damage and loss of life. However, there is no doubt that various social, economic, and cultural aspects of a region can have significant impacts on how the public responds to severe weather warnings and how meteorologists should communicate these warnings. For example,
rural areas of the interior west may not have adequate cell phone service that would allow them to receive Wireless Emergency Alerts (WEA) from the federal government whenever a severe weather warning is issued. Furthermore, members of communities nationwide where English does not serve as the primary language may not understand the severe weather threats that are occurring if they are not fluent in the English language.

The public must also be willing to be “weather aware”, attentive to the potential for severe weather and alert to new developments in forecasts. Severe weather awareness can occur in many different ways with the advents of modern technology. Television has always been a critical source of communicating severe weather information across the nation. Local stations have found innovative ways through the years to provide better ways of communicating severe weather information without interrupting regular programming. ‘Crawls’ would begin to be used during the 1980s to scroll severe weather information along the screen while normal programming continued without interruption (Coleman et al., 2011). ‘Bugs’ would also be used to show what type of warning was in effect or as a map of the coverage area to indicate which counties were under certain types of watches and/or warnings as denoted by the colors of each county on the map (i.e., Red = Tornado Warning, Yellow = Severe Thunderstorm Warning, etc.) (Coleman et al. 2011). The advent of smartphones has also made it easier for people to obtain severe weather information while they are not in front of a television. For example, Wireless Emergency Alerts (WEA) allows the public to receive geographically-targeted, text-like messages alerting them of imminent threats to safety in their area. For example,
if a Tornado Warning is issued for a location where a cell phone is located, an alert similar to a text message will automatically pop up on the smart phone, alerting the citizen of the impending tornado threat.

However, despite these advances in technology in ensuring the public has multiple ways of receiving these life-saving warnings, it is still ultimately up to people themselves if they take these warnings seriously. Unfortunately, it is virtually impossible to assess how the public reacts to severe weather warnings while a severe weather event is actually taking place. It is possible to retrospectively analyze the warning process following severe weather events, reflecting on what worked, what did not, and what can be improved to continuously enhance safety in severe weather.

**Personal Experience in the Warning Process**

During my time as a student in the meteorology program at WKU, I have been fortunate to receive several opportunities that have allowed me to learn from experts in my field in a real-life setting, providing me first-hand exposure to the process of forecasting severe weather. One of the unique aspects of the meteorology field is the multiple different avenues that an aspiring meteorologist can take in not only finding a job but also connecting to the people they serve. While each job within each sector in the field brings its own unique characteristics and challenges, the goal of every meteorologist is to provide scientifically accurate forecasts with the goal of serving the public to protect their lives and their property.
During the summer and fall of 2018, I had the privilege of working at the NWS offices in both Louisville, Kentucky and Nashville, Tennessee as a Student Volunteer. During my time at each of these offices, I was given unique opportunities that not only enhanced my professional skills but also gave me greater insight into how the warning process is implemented. As documented earlier, local NWS offices such as NWS Louisville and NWS Nashville are responsible for issuing severe weather warnings whenever severe weather is an imminent threat or is occurring. During my time at each of these two offices, I gained a full understanding of the fast-paced decision making environment that must exist to ensure an effective and accurate warning process during severe weather events. I also gained perspective on how NWS forecasters relay information to the public during and immediately following severe weather events. This includes data associated with severe weather, such as damage reports, power outage updates from emergency mangers, and a multitude of other sources of information. With this case study, I sought to choose events that would allow analysis of the effectiveness of the warning process itself, but also provide opportunity for sharing my experiences working these specific events, including an ‘inside’ perspective on what worked and what did not in the warning process.

I have also had opportunities during my time at WKU on the ‘receiving end’ of the warning process. As Lead Forecaster for White Squirrel Weather at WKU during the Fall 2018 semester, it was my responsibility to gather the thoughts of nearly a dozen other student forecasters into a brief, concise, and understandable forecast to WKU
officials for decision support regarding major events on campus. These events ranged from concerts on campus to Homecoming festivities and football games among many others. We also provided forecasts to WKU officials whenever potential severe weather posed a threat to campus outside of major campus events. As I gathered input from my fellow forecasters, I also heavily consulted with forecasts from NWS Louisville for each of these events. During severe weather events, we also utilized severe weather warnings issued by NWS Louisville to communicate updates to university officials. Similar to the decision making process in a NWS office during severe weather, the flow of information relayed from NWS Louisville to White Squirrel Weather to university officials must also be rapid, especially in the immediate aftermath of a severe weather event. Fast yet effective communication is critical for White Squirrel Weather in ensuring that the university has current and timely information on severe weather threats and any updates from the NWS following the event should recovery efforts be necessary on campus. Failure to have swift, efficient communication using information from NWS Louisville could negatively affect the ability to mitigate potential severe weather impacts on campus.

As documented earlier, television is the traditional option for many people receiving severe weather information from the NWS during an event. While the sources of information continue to expand with advances in technology, local television stations still place great emphasis on weather broadcasts, especially during times of severe weather. In an ideal scenario, local television stations in a given area have a strong
relationship with their local NWS office. Having this strong relationship between NWS offices and local television stations is critical is ensuring that key warning messages from the NWS are passed along to the public via television stations, with the ultimate goal of protecting the public from any dangerous weather. Local television stations and NWS forecasters should work collaboratively toward the mutual goal of protecting the people they serve. I have visited numerous television stations during my time at WKU, including stations in Knoxville, Tennessee; Lexington, Kentucky; Nashville; and Louisville. I have also had the opportunity to be a meteorology intern at WBKO in Bowling Green. All of the meteorologists at each of these stations will attest to the importance of having a strong relationship with each of their local NWS offices in ensuring effective communication of weather warnings to the public. To further solidify this relationship, NWS operates an online chat exclusively for members of the media, local emergency managers, and surrounding NWS offices. This chat is incredibly useful during severe weather, as NWS forecasters can pass along warning information to members of the media before the actual warnings are issued, thus further expediting the warning process when time is of the essence. NWS forecasters can also use this chat as a faster way to communicate additional information pertaining to the severe weather event, including damage reports, photos, and videos. Without this strong connection between NWS offices and local television stations, the communication aspect of the severe weather warning process could be hindered, potentially placing the public at greater risk.
CHAPTER TWO

THE CASE STUDY

Part I: Event Selection

For this case study, six severe weather events over the course of five days in calendar year 2018 were selected. These six events occurred in the NWS Louisville and/or NWS Nashville CWAs. Choosing recent events provides the best opportunity for reanalysis of past severe weather events with the greatest application to the current technology and products available to meteorologists across the industry, including the NWS. While analyzing events further in the past (i.e., prior to 2018) can prove useful in providing better warnings to the public for similar events in the future, choosing more recent events not only capitalizes on improving the warning process using current technology, but also draws on reflections from meteorologists who worked these events, specifically regarding factors that led to the event being successfully or unsuccessfully warned. The six events chosen for analysis in this case study as well as the corresponding NWS office (Louisville or Nashville) responsible for each event are outlined in Table 2.
Table 2

**Severe Weather Events Chosen for Case Study**

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
<th>NWS Office Being Analyzed</th>
</tr>
</thead>
<tbody>
<tr>
<td>February 24, 2018</td>
<td>Deadly tornado producing storm in Logan County, KY</td>
<td>Louisville</td>
</tr>
<tr>
<td>February 24, 2018</td>
<td>Tornado producing line of storms near Clarksville, TN</td>
<td>Nashville</td>
</tr>
<tr>
<td>June 26, 2018</td>
<td>Spin-Up tornado along a line in Louisville, KY</td>
<td>Louisville</td>
</tr>
<tr>
<td>July 20, 2018</td>
<td>Severe weather outbreak across NWS Louisville area</td>
<td>Louisville</td>
</tr>
<tr>
<td>September 24, 2018</td>
<td>Unwarned tornado touchdown in Cannon County, TN</td>
<td>Nashville</td>
</tr>
<tr>
<td>November 5-6, 2018</td>
<td>Deadly tornado along a line in Christiana, TN</td>
<td>Nashville</td>
</tr>
</tbody>
</table>

Another consideration in choosing these six events was my personal connections with each of these events. During all of these severe events with the exception of February 24, I was working at the NWS offices in Louisville and Nashville as a student volunteer. This unique personal experience provided me with firsthand access to the decision-making that takes place in the warning process at the NWS as severe weather events materialize. My personal experience with most of these events allows me to share my firsthand account of what I felt worked and what could be improved in future events. This unique understanding of a NWS office operates in times of severe weather lends additional validity to this case study that other case studies of this nature may be unable to provide.

A third reason that these six events were chosen is their regional relevance. Each of these events caused damaging weather in the Ohio Valley region, including areas close to Bowling Green. The NWS offices in Louisville and Nashville are responsible for
issuing life-saving warnings for residents in this region. NWS Louisville, for example, is responsible for warnings in Bowling Green, as well as Louisville and Lexington, Kentucky. Whenever severe weather is approaching Bowling Green, it is the responsibility of the NWS Louisville office to ensure that the people of Bowling Green (including WKU campus) receive timely alerts to prepare for impending dangerous weather. NWS Nashville has the same responsibility not only for Nashville, but also for major Tennessee cities including Murfreesboro and Clarksville among others. It is important for us to understand the process of how our local NWS offices issue severe weather warnings and how effective their warnings are. While case studies of other NWS offices across the country and their warning process could provide useful information for improving the process nationally, the focus of this case study is on the warning process for our local NWS offices and how effective the process is as it relates to the types of severe weather common to our area. The types and modes of severe weather that take place in different areas of the country can vary drastically from coast to coast. Because of this, the warning process for each office can be different as well even if the types of warnings and their criteria stay the same nationwide.

Part II: Analysis Methodology

Each of these six events will be analyzed in a similar manner. A brief overview of the meteorological setup for each event will provide context for the ingredients in place that led the event to occur. A full analysis of select storms from each event will follow. Due to the widespread spatial scale of some of the events, the focus of the analysis will be largely focused on the most significant storms of each event. Significant refers to the
severity or strength of the storms (i.e., the strongest tornadoes), the storms that produced
the most substantial damage along its path, or the greatest effects on life and property.
The analysis is focused heavily on storms that either produced tornadoes or had Tornado
Warnings issued by the local NWS offices over the course of the event. While many of
these events also had additional damaging winds and Severe Thunderstorm Warnings that
were not the result of tornado activity, Tornado Warnings and tornado activity are much
less common and typically (but not always) produce more significant damage, making
them easier to be analyzed for a case study.

The reanalysis of these events will be based heavily on archived radar data using
the Gibson Ridge 2 Analyst (GR2A) radar software. Various radar products such as Base
Reflectivity (BR), Base Velocity (BV), Storm Relative Velocity (SRV), Correlation
Coefficient (CC), and Normalized Rotation (NROT) will be used to analyze these storms
and the warning process by both NWS Louisville and NWS Nashville. For a detailed
analysis of the roles of each of these products, refer to Chapter One. The evolution of the
structure of the storms, their progression, and the warnings issued will be carefully
analyzed. In addition, any information critical to the evolution of the storm over the
course of its life cycle will also be provided, including but not limited to damage images,
NWS warning bulletins, and radar annotations signifying critical aspects of the storms
that led to warnings being issued or adjusted. Verification statistics will also be
discussed, providing a quantitative analysis of what worked and what did not work with
the warning process as these storms occurred. For a detailed description of these
verification statistics, refer to Chapter One. A qualitative analysis will also be provided,
discussing the characteristics of the storms as they evolved and any experiential
reflections from my work with each event, including my perceptions of what was successful and what could be improved in the warning process for these events. Once all events have been analyzed, a discussion of the general trends with these six events will follow, outlining key positive and negative takeaways from the warning process for each of these events. These takeaways will then be used to raise questions about key improvements that can be made for similar events across both NWS offices in the future.

Part III: A Disclaimer

Before the case study begins in earnest, I wish to reiterate the true purpose of this case study. The purpose of this case study is to analyze the effectiveness of the NWS warning system across Kentucky and Tennessee, specifically at the NWS Louisville and Nashville offices. The case study is designed to show what each of these offices did well during select severe weather events in 2018 and where opportunities for improvement exist for severe weather events in the future. While some events could shed light on some deficiencies in the warning process at each of these offices, it is meant in no way to criticize or diminish the reputation of either of these offices. Both the NWS Louisville and NWS Nashville offices are recognized as being two of the strongest NWS offices in the country. Those who work at each of these offices are skilled and talented in their field and have served as a great source of support for the WKU meteorology program and its students. Their knowledge of meteorology and their skills as forecasters have undoubtedly saved lives for many years. This case study provides retrospective review to identify areas of the warning process that could be improved upon in the future, enabling the meteorology industry to better serve the public and ultimately save more lives.
Part IV: The Events

Event #1: February 24, 2018 (Logan County, KY Supercell)

On Saturday, February 24, 2018, the environment across the Ohio and Mississippi River Valleys was primed for a widespread severe weather event. Forecasters had been observing the potential for severe weather several days in advance. The Storm Prediction Center outlined an area where the potential for severe weather existed on the Day 4 Convective Outlook on Wednesday, February 21. While it is not uncommon for Day 4 Convective outlooks to indicate areas of potential severe weather three days out, these outlooks indicate a higher confidence of severe weather potential far in advance that should raise awareness in forecasters and the public alike. This initial Day 4 outlook was a 15 percent (also known as a Slight Risk) chance of severe weather stretching from Hopkinsville, Kentucky and Nashville, Tennessee and points southwestward across the Arklatex region (Figure 2.1).

Figure 2.1: Day 4 SPC Convective Outlook, issued February 21, 2018. (Courtesy SPC).
In this Day 4 Outlook, SPC forecasters were already suggesting that “a forced line of potentially strong to severe storms might evolve in [the] vicinity of the cold front over northeast TX, before spreading into the lower MS and TN Valley regions,” (Dial, 2018). In other words, a line of strong to severe storms would likely develop over the Arklatex region and drift northeastward into Arkansas, northern Mississippi, Tennessee, and southwestern Kentucky Saturday along the passage of a cold front. By Day 2, Friday, February 23, confidence was increasing that a widespread severe weather event would take place across the mid-South on Saturday. The SPC hence upgraded much of the same Slight Risk area from Day 4 into an Enhanced Risk (level 3 out of 5) for severe weather Saturday. The Enhanced Risk zone stayed virtually identical in the early morning updates on Saturday the 24th, the morning of the event. However, a 10 percent risk zone for tornadoes was also denoted in the same general area as the Enhanced Risk area, primarily from Paducah, Kentucky southwest towards the Arklatex. These two risk zone maps can be seen in Figure 2.2 below. The black hatched marks in the tornado risk zone indicate strong to potentially violent tornadoes are also possible in this area as well.
SPC forecasters had the same general mindset with how the severe weather setup would evolve but did note one key concern with the evolution of this event. Earlier in the morning, a line of strong thunderstorms had developed ahead of the warm front across southern Kentucky, affecting Bowling Green. Because of this, a heavy cloud cover was
present across much of the area through the morning and early afternoon hours on Saturday. This limited the amount of sunshine the area received at the surface, thus keeping temperatures cooler than anticipated and limiting the instability of the atmosphere, reducing the potential of severe storm development. On the other hand, SPC forecasters also noted the strong veering wind profile in the upper levels of the atmosphere. The clockwise change in wind direction associated with veering winds indicates a high amount of shear in the atmosphere, which is conducive for storms to develop rotation. The rotation could eventually lead to tornadoes should storms develop either ahead of the line during the afternoon or along the line itself later in the evening (Goss/Marsh, 2018). Indeed, despite the limited instability due to cloud cover throughout the afternoon, a severe storm developing northwest of Nashville during the mid-afternoon hours led to a tornado producing supercell that is the subject of the first event of this case study.

At 3:15 PM Central Time on February 24, a Tornado Watch was issued for all of western Kentucky and much of western Tennessee ahead of the line of severe thunderstorms that had developed to the southwest and was forecast to move into the area later in the evening. In this watch, no counties controlled by NWS Louisville were included and only four of the 38 counties NWS Nashville controls were in the watch area. While a watch was likely to be issued for much of the rest of the area these two offices control later in the evening once the severe line of storms got closer, the threat was still fairly low at the time. There was a lack of instability resulting from leftover cloud cover from the morning round of storms. However, by the time this Tornado Watch was issued to the west of the study area, a severe thunderstorm had developed in Montgomery
County, Tennessee near Clarksville. By 3:15 PM, the storm was already exhibiting characteristics of a discrete supercell, with a ‘hook echo’ feature commonly found in supercells. Base Reflectivity (BR) detects this feature very well in Figure 2.3 (left). Base Velocity (BV) also shows the broad rotation beginning to develop with this supercell to the south of Clarksville over the same area where the hook echo is observed in BR imagery (Figure 2.3-right). At this moment, the rotation was not strong enough to warrant a Tornado Warning, prompting NWS Nashville to stay with a Severe Thunderstorm Warning as it progressed northeastward approaching the Kentucky-Tennessee state line.

Figure 2.3: Base Reflectivity (left) and Storm Relative Velocity (right) radar imagery from NWS Nashville radar at 3:15 PM showing the severe storm beginning to take on a hook echo signature and developing rotation to the south of Clarksville, TN (circled).

By 3:30 PM, the storm had lost its organization and had weakened considerably over the last several radar scans. Thus, NWS Nashville dropped the Severe Thunderstorm Warning for Montgomery County and issued no further warnings with this storm. At 3:47 PM, however, radar detected a Tornado Vortex Signature (TVS) with this storm near the community of Adams, Tennessee in Robertson County. This TVS stayed on radar for
another scan at 3:50 PM (Figure 2.4) but had disappeared by the next scan at 3:53 PM.

NWS Nashville chose not to issue a Tornado Warning despite the TVS, the increased rotation, and storm strength observed on BR and BV products.

![Radar Imagery](image)

Figure 2.4: Base Reflectivity (left) and Storm Relative Velocity (right) at 3:50 PM, February 24, 2018 with an associated tornado vortex signature near Adams, TN (green triangle). NWS Nashville opted with no warning as the storm moved into Kentucky.

A close-up of the radar imagery shows the rotation continuing to intensify and maintain its strength as it crosses the state line into Logan County, Kentucky at 3:55 PM, turning control of the warnings for this storm to NWS Louisville. The strongest rotation at this point was located to the west of Adairville, Kentucky, as circled in Figure 2.5.

NWS Louisville decided to only go with a Severe Thunderstorm Warning at 3:58 PM for 60 MPH wind gusts and quarter sized hail, the minimum criteria for issuing such a warning.
Figure 2.5: Base Reflectivity (left) and Storm Relative Velocity (right) showing the tornadic circulation crossing the Kentucky-Tennessee state line at 3:55 PM (circled). Despite the rotation, NWS Louisville issued only a Severe Thunderstorm Warning at 3:58 PM.

The supercell continued to intensify as it trekked across southern Logan County, beginning to exhibit the strongest hook echo seen thus far in the storm’s life cycle at 4:03 PM. Rotation was also still present with this storm right in the same area as the hook echo, suggesting this was becoming a classic supercell with a potentially strong tornado developing at any moment, as seen in Figure 2.6.
Figure 2.6: Base Reflectivity (left) and Storm Relative Velocity (right) at 4:03 PM. The hook echo appears to be intensifying and the storm appears to be taking the form of a classic supercell. No Tornado Warning has been issued at this point.

At this point, NWS Louisville had received no reports of tornadic activity or damage from this storm. However, NWS Nashville had just received a report from the public of possible tornado damage in extreme northern Robertson County, in the exact spot that the supercell had crossed the Kentucky-Tennessee state line. BR imagery shows a spike in returns within the hook echo at 3:58 PM, just after the supercell had crossed into Kentucky. This pink return in the hook echo could perhaps indicate debris being lofted into the sky from the tornado. Other radar products were inconclusive in determining if this was indeed debris.

At the time this call was received from NWS Nashville, the WKU meteorology program was coincidentally in the Nashville office on a prescheduled office tour. From my personal recollections of that day, I distinctly recall a forecaster hanging up the phone in frustration, realizing that they had not issued a Tornado Warning for Robertson County and that the tornado touchdown had gone without any warning. Upon being notified by
NWS Nashville of the damage in Tennessee, NWS Louisville issued a Tornado Warning for Logan and Simpson County, Kentucky (just south of Bowling Green) at 4:06 PM. However, it appeared the warning was too late. The tornado was still on the ground and doing damage. Indeed, storm surveys of damage in both Robertson and Logan Counties the day after the tornado indicated that the tornado had been on the ground 12 minutes prior to a Tornado Warning being issued and four minutes before a Severe Thunderstorm Warning was issued. The warning process had failed.

The supercell intensified considerably as it tracked eastward across southern Logan County. The hook echo feature was at its strongest as it was moving into southeastern Logan County at 4:11 PM. The rotation was also very tight in the same area as the hook echo, with inbound winds wrapping into the circulation in green pixels from the northeast and outbound winds wrapping around the circulation in red pixels form the southwest in BV imagery in Figure 2.7.

Figure 2.7: Base Reflectivity (left) and Storm Relative Velocity (right) at 4:11 PM. The tight green and bright red pixels on Storm Relative Velocity (circled) indicate strong rotation associated with this storm as it moves across southern Logan County.
Although the storm did not look as organized on BR imagery at 4:21 PM, the rotation was still present. However, the storm was now taking a left hand turn, tracking more northeastward towards southern Warren County and southern Bowling Green instead of into Simpson County (Figure 2.8). As a result, NWS Louisville issued a new Tornado Warning to include the city of Bowling Green.

![Figure 2.8: Base Reflectivity (left) and Storm Relative Velocity (right) at 4:21 PM. The rotation with the storm continues to progress northeastward (circled), prompting a new Tornado Warning for Bowling Green.](image)

As the storm progressed northeastward into Warren County, it began to lose its organization and the rotation associated with the tornado that has moved across Logan County 30 minutes earlier. By 4:40 PM, the rotation was virtually non-existent as the storm moved into eastern Warren County, but NWS Louisville kept the warning in place until 4:45 PM in the event the storm reintensified as it did when it initially produced the tornado in Robertson County, Tennessee. This did not materialize and the Tornado Warning was allowed to expire at 4:45 PM as scheduled.
The storm, albeit in a weaker state, did continue into rural areas of northeastern Warren County with some rotation still associated with it. However, the rotation was not strong enough to detect using Storm Relative Velocity, but was enough to be seen using the Normalized Rotation (NROT) product. Figure 2.9 shows NROT values over 1.00 in the green pixels, again collocated with the hook echo feature that is still apparent in this now weakened supercell. The storm continued to exhibit rotation, but never enough rotation for NWS Louisville to reissue another Tornado Warning.

Unfortunately, a tornado did touch down along the Warren-Barren County line with this storm at 5:19 PM, producing EF-1 damage (Figure 2.10). The warning process had once again missed another tornado with the same supercell storm.
When this supercell’s path was surveyed by NWS Louisville, it was determined the first tornado produced EF-2 damage, a strong tornado with winds upwards of 135 MPH at its peak. It touched down on the Robertson/Logan County line at 3:54 PM, 12 minutes before a Tornado Warning was issued, and continued northeastward before lifting in Logan County north of Adairville, Kentucky at 4:12 PM. This storm produced significant damage to homes in its path, ranging from roof damage to foundation damage. At one of these homes in Logan County, an elderly woman lost her life as a result of falling debris as the tornado hit. The EF-2 strength was determined to be in this same area, with “debris thrown up 500 yards with a width of 250 to 300 yards in a farmer’s field,” (NWS Louisville, 2018). Damage photos taken from the survey of the home of the deceased victim can be seen in Figure 2.11 (left). The tornado was also captured by a Logan County resident near Keysburg (Figure 2.11-right). The second tornado in Warren
County was an EF-1, with winds of 95 to 100 MPH and on the ground for only two minutes.

Figure 2.11: Left: Damage from the home of the deceased victim from the EF-2 tornado in Logan County (Courtesy NWS Louisville). Right: The EF-2 tornado on the ground near Keysburg, KY (Courtesy Lori Henderson via NWS Louisville).

When analyzing the warning process associated with this supercell, it is clear that there were several critical errors that potentially resulted in this being a deadly tornado. The first error of note was the decision by NWS Nashville forecasters to not issue any warning of any kind with the storm after 3:30 PM. The storm did not exhibit severe characteristics that would prompt the issuance of a new warning for almost 20 minutes after the previous Severe Thunderstorm Warning had expired at 3:30. However, given the combination of the Tornado Vortex Signature being displayed on radar at 3:47 and 3:50 PM and the increased rotation near Adams, Tennessee and the Kentucky-Tennessee state line, a warning from NWS Nashville was likely warranted before it crossed into Kentucky and NWS Louisville’s coverage area. This is especially true given an environment that was conducive for tornadic development with any storm that fired off that afternoon. One reason for the missed warning could have been the storm’s close proximity to the state line. Given the storm’s rapid northeastward progression towards
Kentucky and out of their coverage area, perhaps NWS Nashville decided to hold off on issuing any further warnings with the storm thinking that the rotation would be fully into Kentucky by the time it was strong enough to issue a Tornado Warning, which would then be the decision of NWS Louisville. Of course, that did not prove to be the case as the tornado touched down just inside Tennessee, making it technically a ‘missed’ Tornado Warning for NWS Nashville.

The lack of a further warning for this storm by NWS Nashville eventually resulted in a chain reaction that led to a significant delay in the issuance of warnings by NWS Louisville that proved to be fatal. As documented in the analysis of this event, the tornado touched down just inside Tennessee at 3:54 PM. Rotation was strong enough at this point on radar where a Tornado Warning would be a viable decision by NWS Louisville, especially given the environmental conditions in place. Nonetheless, NWS Louisville only issued a Severe Thunderstorm Warning at 3:58 PM, with no indication that a tornado was possible, something commonly used in Severe Thunderstorm Warning messages today. It was clear over the next several radar scans that the rotation was not weakening but was in fact strengthening. Yet no Tornado Warning was issued until 4:06 PM. By the time the first Tornado Warning was issued with this storm, the tornado had been on the ground causing damage for 12 minutes.

Missing tornado touchdowns is not uncommon with smaller, spin-up tornadoes that occur along a line of severe thunderstorms, as we will see later in this case study. However, missing tornado touchdowns on supercell storms of this nature are much more rare and more egregious, given the rotation is much easier to detect in supercell storms compared to rotations along a line of storms. Considering this, the 12-minute gap
between initial tornado touchdown and initial Tornado Warning issuance is extremely concerning, especially on a day where the environment was sufficient for tornadic development. To add to the concern, this tornado resulted in a fatality in Logan County that occurred prior to that Tornado Warning being issued. We can never know if this fatality could have been prevented had a Tornado Warning been issued earlier. What is clear from this event is that the lack of issuance of any further warnings by NWS Nashville contributed to a significant delay in NWS Louisville issuing timely warnings as the storm crossed into Kentucky. Several questions could be raised as it relates to the coordination of meteorologists at two NWS offices as a storm crosses state lines.

- Was there communication between the two offices as the storm was preparing to cross state lines? If so, what was being discussed?
- Did NWS Nashville “let go” of the storm too early because it was almost into Kentucky, handing control over to NWS Louisville before it left Tennessee?
- Why did NWS Louisville wait so long in issuing warnings with this storm given the environment in place and with this storm being the only severe storm in their coverage area?
- Did NWS Louisville not issue any warnings in advance of the storm because there were no warnings issued by NWS Nashville?
- **Big picture question: How can neighboring NWS offices better coordinate in the warning process with severe storms that are crossing NWS coverage area boundaries?**
Event #2: February 24, 2018 (Clarksville, TN Tornadoes)

As the evening progressed, the main line of storms that was of greatest concern on this day was beginning to march towards middle Tennessee and southern Kentucky. Although several reports of damaging winds had taken place along the line across Arkansas and Mississippi, the overall volume of severe weather reports was fairly low as the line moved into west Tennessee. Nonetheless, the line was still severe with numerous Severe Thunderstorm Warnings. Considering the high amount of wind shear still present in the atmosphere, a tornado threat along the line was still possible. As such, the SPC issued a new Tornado Watch at 8:25 PM that included much of the NWS Nashville and NWS Louisville coverage areas (Figure 2.12). This watch included Nashville, Bowling Green, Clarksville, and the areas impacted by the deadly supercell tornado discussed in Event #1 earlier in the day.

Figure 2.12: Tornado Watch issued by the SPC at 8:25 PM February 24, 2018.

Eight minutes prior to this watch being issued, NWS Nashville issued their first Tornado Warning of the night for a line of severe thunderstorms with embedded areas of
rotation capable of producing brief tornadoes. At 8:29 PM, a new Tornado Warning was issued to include Clarksville, Tennessee.

The rotation along the broken line of severe storms was very difficult to pick out. However, Storm Relative Velocity (SRV) shows a weak area of rotation southwest of the community of Indian Mound at 8:36 PM. The next couple of scans would become a forecaster’s nightmare. For an unforeseen reason, the SRV imagery went blank at 8:39 PM. Forecasters on duty no longer had a key tool at their disposal to determine the strength of any rotations embedded in the line. Luckily, the SRV product returned a few moments later at 8:45 PM. What was initially a weak rotation near Indian Mound had now blossomed into two distinct rotations. The first rotation was still in a weakened state. However, a second rotation was now located just southeast of the initial rotation and located northeast of Cumberland City. This rotation had a Tornado Vortex Signature (TVS), suggesting a tornado could be on the ground (Figure 2.13).

Figure 2.13: Base Reflectivity and Storm Relative Velocity at 8:46 PM shows a strong rotation with a Tornado Vortex Signature to the southwest of Clarksville.
Four panel radar analysis, introducing Normalized Rotation (NROT) and Correlation Coefficient (CC), shows significant rotation with this TVS, with NROT values over 2.00, indicating significant rotation. CC had no minimum values of interest at this point, suggesting that if a tornado was on the ground, it was not yet lofting any debris into the air (Figure 2.14). The TVS was still present on the rotation for the next several scans as the strong rotation was now approaching the city of Clarksville.

![Figure 2.14: Base Reflectivity, Base Velocity, Normalized Rotation (bottom left), and Correlation Coefficient (bottom right) at 8:46 PM. NROT values above 2.00 are observed near the area of rotation southwest of Clarksville (circled). However, correlation coefficient did not seem suggest debris being lofted at this moment.](image)

At 8:55 PM, CC was now picking up on a minimum collocated with areas of strongest rotation on NROT and SRV. A tornado was now on the ground and lofting debris into the sky (Figure 2.15). With this updated radar scan, NWS Nashville issued a new Tornado Warning at 8:57 PM, upgrading it to a “Particularly Dangerous Situation,” a phrase only used when a tornado is confirmed to be on the ground and approaching a
heavily populated area (NWS Nashville, 2018). This upgraded Tornado Warning is indicated by the pink box in the Gibson Ridge 2 Analyst software shown in Figure 2.15.

As this now confirmed tornado raked across the northwest side of Clarksville, a new tornadic circulation developed just to the southeast of downtown Clarksville. This new circulation now became the dominant circulation, producing a TVS on radar at 9:02 PM as it raced to Interstate 24 northeast of downtown Clarksville and towards the heavily populated suburbs (Figure 2.16). The tornado crossed I-24 at 9:04 PM.
Figure 2.16: Base Reflectivity and Storm Relative Velocity at 9:02 PM shows the original tornadic circulation over Clarksville weakening while a new circulation begins to develop very close to Interstate 24 with a Tornado Vortex Signature (circled).

Just as quickly as it had developed, the second tornado-producing rotation along I-24 was virtually non-existent by 9:10 PM. However, yet another rotation would develop, this time to the southeast of the I-24 rotation southwest of the community of Adams, Tennessee (Figure 2.17). By 9:18 PM, the rotation was moving right over Adams, but evidence was inconclusive as to whether or not a third tornado in the span of 30 minutes had developed. NWS Nashville issued a new Tornado Warning further east for Robertson County, Tennessee, but backed off from the “Particularly Dangerous Situation” wording used with the first two tornadoes near Clarksville.
Figure 2.17: Four Panel radar at 9:18 PM showing a third tornadic circulation forming over the community of Adams, TN.

By 9:22 PM, just as the rotation seemed to be weakening, CC showed a minimum developing to the northeast of Adams in Robertson County, suggesting debris being lofted from a possible tornado. The rotation and CC minimum would begin to fade over the next couple of radar scans and the Tornado Warning expired at 9:45 PM.

Storm surveys following the event indicated that those three rotations detected on radar did indeed produce tornadoes. The first circulation to the northwest of Clarksville produced an EF-1 tornado with winds of 105 MPH at 8:50 PM. The second tornado that crossed I-24 was rated an EF-2 with winds of 125 MPH at 9:03 PM. This second tornado shifted an entire single-family two-story home off of its foundation. Only two injuries were reported. The third and final tornado was an EF-1 with 95 MPH winds and touched down at 9:19 PM with primarily barn and outbuilding damage. Outside of the two
injuries with the I-24 tornado, there were no other injuries or fatalities with any of the three tornadoes.

Despite the issues with the warning process with the supercell earlier in the day, the warnings issued for these three tornadoes near Clarksville later in the evening were issued very well. The first Tornado Warning for Montgomery County (Clarksville area) was issued at 8:29 PM, 21 minutes before the first tornado touchdown at 8:50 PM. This means that residents had 21 minutes of lead time from the time they received the warning and took shelter to the time the first tornado touched down. As discussed earlier, accurately issuing Tornado Warnings along a line of severe thunderstorms is extremely difficult due to the quick, pulsing nature of spin-up tornadoes along the line. Considering this, the 21-minute lead time for Montgomery County residents between the first warning and the first tornado touchdown is quite an accomplishment. The extension of the first Tornado Warning, emphasizing that this was now a “Particularly Dangerous Situation” with a tornado on the ground, further reinforced that this was a situation that the public should take seriously. After already being under a Tornado Warning for nearly 30 minutes by the time of the new warning, people could become frustrated with staying in shelter for a long period of time and no confirmed reports of actual tornadoes or damage. The ‘cry-wolf’ effect discussed earlier could come into play. However, the new Tornado Warning with a more aggressive and serious tone emphasized to the public that this situation was dangerous and not something to ignore, likely keeping people in shelter and safe. Of note, the third tornado that touched down near Adams in Robertson County had a 22-minute lead time from that same Tornado Warning that was issued to reinforce the danger from the Clarksville tornado at 8:57 PM.
The plentiful lead time from each of these Tornado Warnings with the three tornadoes near Clarksville showed how effective the warning process can be and is something that should be recognized. However, an element that could be debated is the wording of the warning text with the second warning issued at 8:57 PM. The NWS Nashville stated that the tornado that was on the ground was “a confirmed large and extremely dangerous tornado,” (2018). Furthermore, NWS Nashville also called this a “Radar Confirmed Tornado” based on the Correlation Coefficient minimum detected northwest of Clarksville with debris being lofted from the first tornado. It is clear that the first tornado was on the ground at the time this warning was issued. However, what is not clear is whether or not this tornado was “large and extremely dangerous,” as NWS Nashville described it (Figure 2.18) In the end, this tornado was only 150 yards wide at its peak, or 1.5 football fields wide.
The National Weather Service in Nashville has issued a

* Tornado Warning for...
Northeastern Montgomery County in Middle Tennessee...
Northwestern Robertson County in Middle Tennessee...

* Until 930 PM CST

* At 856 PM CST, a confirmed large and extremely dangerous tornado was located near Clarksville, moving northeast at 35 mph.

This is a PARTICULARLY DANGEROUS SITUATION. TAKE COVER NOW!

HAZARD...Damaging tornado.

SOURCE...Radar confirmed tornado.

IMPACT...You are in a life-threatening situation. Flying debris may be deadly to those caught without shelter. Mobile homes will be destroyed. Considerable damage to homes, businesses, and vehicles is likely and complete destruction is possible.

* The tornado will be near...
Clarksville and Clarksville around 900 PM CST.

Other locations impacted by this tornadic thunderstorm include Cedar Hill and Adams.

PRECAUTIONARY/PREPAREDNESS ACTIONS...

To repeat, a large, extremely dangerous and potentially deadly tornado is on the ground. To protect your life, TAKE COVER NOW! Move

Figure 2.18: The bulletin text of the Tornado Warning issued by NWS Nashville for Clarksville, TN at 8:57 PM. The “confirmed large and extremely dangerous tornado” text could be misleading if the size of the tornado has not been confirmed by the naked eye and could perhaps be interpreted as a “fear factor” more than being informative.

While that may seem large, that is actually fairly small compared to larger tornadoes seen with supercells in the Great Plains. Using such phrasing to describe the size of a tornado when it cannot be confirmed with the naked eye may induce some sort of a “fear factor” in the public that is more designed to scare the public into taking shelter rather than being informative. In addition, while the Correlation Coefficient can be very useful in determining whether or not debris is being lofted with a tornadic circulation, the
tool itself may not necessarily confirm a tornado on its own, but merely suggest that a tornado is on the ground. With this in mind, here are a few questions to consider from this event.

- Should the NWS consider changing the wording on Tornado Warnings with confirmed tornadoes that does not include a descriptive on the tornado’s size?
- Is there such a thing as a Radar Confirmed Tornado? How can this be conveyed differently?
- Can we really confirm a tornado unless it is seen by the naked eye?
- **Big Picture Question:** How can NWS meteorologists properly communicate the urgency of a situation where they believe and radar shows evidence of a confirmed tornado even though a tornado has not been confirmed by someone seeing one with their own eyes?
Event #3: June 26, 2018 (Spin-Up Tornado Along a Line in Louisville, KY)

During the morning hours of Tuesday, June 26, 2018, a line of strong to severe storms that resulted in widespread wind damage across Missouri and Illinois overnight was beginning to make its way into southern Indiana and north-central Kentucky. This line of storms (commonly referred to as a bow echo for its bow-shaped characteristics) seemed to hold together far longer than expected and continued to maintain its intensity throughout the late morning and early afternoon. This came as a surprise to the SPC, who had only placed NWS Louisville’s area in a Marginal Risk (Level 1 out of 5) for severe weather the morning of this event. Nonetheless, the bow echo continued to produce wind damage along its path, forcing the SPC to issue a Severe Thunderstorm Watch for virtually all of NWS Louisville’s area at 10:25 AM that morning.

Figure 2.19: As the bow echo of severe storms races from Illinois into Kentucky and southern Indiana, the SPC issued a Severe Thunderstorm Watch for much of the NWS Louisville coverage area at 10:25 AM Eastern Time.
As the bow echo began to move into the NWS Louisville coverage area just before 1:00 PM, the line was beginning to lose its structure, perhaps suggesting that the storms may be in a weakening state. NWS Louisville still had numerous Severe Thunderstorms Warnings issued across southern Indiana and northern Kentucky for 60 to 70 MPH damaging winds. A Severe Thunderstorm Warning was issued for the city of Louisville at 1:04 PM as the system had begun to reorganize and intensify. Base Reflectivity shows this reorganization as the line crosses the Ohio River into the city of Louisville at 1:05 PM.

![Figure 2.20: Base Reflectivity at 1:05 PM. The isolated storms ahead of the line merging with the line would play a key role in the development of brief tornadoes later in the day.](image)

Notice the storms just ahead of the line in central Louisville. These storms would begin to merge into the bow echo as it crossed into the city. From a general standpoint,
isolated storms ahead of a line of storms that merge with the line typically lead to a brief period of rotation along the front edge of the existing line, potentially leading to the development of a spin-up tornado. These spin-up tornadoes are similar to the ones analyzed in Event #2 earlier, but just form differently. By 1:30 PM, these isolated storms had merged with the existing line of storms centered right over the city of Louisville. Some weak rotation was beginning to develop along the Ohio River just to the east of downtown Louisville, but were not a source of immediate concern.

Figure 2.21: Base Reflectivity and Storm Relative Velocity at 1:32 PM. Broad rotation is beginning to form along the Ohio River to the east of downtown Louisville (circled).

The broad, weak rotation continued to slowly move across the northeastern sections of the Louisville suburbs. By 1:40 PM, the rotation began to tighten considerably as observed on Storm Relative Velocity and Normalized Rotation, specifically to the west of Crestwood and to the north of Middletown. Just four minutes later at 1:44 PM, the rotation was now very tight on the Jefferson-Oldham County line in northeast Louisville.
Figure 2.22: Storm Relative Velocity (right) shows strong rotation along the Jefferson-Oldham County line near Crestwood, KY (circled).

In response, NWS Louisville issued a Tornado Warning for parts of northeastern Jefferson County as well as Oldham and Shelby Counties to the east at 1:46 PM.

Figure 2.23: Normalized Rotation (NROT) shows the strongest rotation near Crestwood, KY as a Tornado Warning is issued for the northeastern suburbs of Louisville.
Within six minutes, however, the tornadic circulation had completely dissipated and the Tornado Warning was quickly cancelled. The warning itself was only in effect for 14 minutes, which is very low compared to most Tornado Warnings.

Figure 2.24: Storm Relative Velocity shows the rotation had become non-existent within 10 minutes after the Tornado Warning was issued.

A storm survey the day following the event confirmed a tornado touchdown in the same general area of the rotation seen on radar in the northeastern part of Jefferson County. The tornado was rated an EF-1 with winds of 90 MPH and primarily caused tree damage with some minor home damage in certain areas along the path. NWS Louisville officially determined the tornado touched down at 1:44 PM, two minutes prior to the Tornado Warning issuance. In other words, the Tornado Warning was two minutes late as it relates to the tornado touching down itself. There was also extensive straight-line wind damage as a result from the line of storms themselves, as seen in the tree damage near Crestwood. This straight-line wind damage was not the result of a tornado.
Accurately issuing Tornado Warnings for rotations embedded in a line is incredibly difficult. As we saw with Clarksville tornadoes in Event #2, one rotation along the line may fall apart while a second or even third rotation can form in the general area where the first rotation dissipated. The randomness and unpredictability of these embedded rotations along a line is what makes issuing Tornado Warnings so difficult. In the case of the June 26 event, the threat of tornadoes embedded along the line itself was virtually zero. The only threat that existed for a tornado would have been the result of an isolated storm merging with a line as we saw in Louisville, a threat that seemed so isolated that there was no mention of the potential in any SPC severe weather outlooks the day of the event.

At the office that day, the rotation that developed over the northeastern suburbs of Louisville came as quite a surprise to the forecasters on duty given the low threat for tornadoes. Nonetheless, the forecasters on duty decided to go with a brief Tornado Warning based on how rapidly the rotation had developed on radar and the fact that the rotation would not last too long, especially once the isolated storm ahead of the line had become fully merged with the line. While the short duration of the Tornado Warning was verified, with the rotation fully disappearing within 10 minutes of the warning being issued, the questions becomes whether or not there is really any need to issue a short-term Tornado Warning on an already severe line of thunderstorms. In some cases, severe straight-line winds can cause the same amount or even greater damage than a weak tornado such as the tornado in this event. The public may also wonder what the point is in issuing a 15-minute Tornado Warning if the line is already severe and has Severe
Thunderstorm Warnings along the entire length of the line. With this in mind, here are a few questions to consider for similar scenarios in the future.

- Should there be some set criteria for the duration of severe weather warnings with the NWS (i.e., minimum 20-minute warnings)?
- Are short-term Tornado Warnings necessary in a situation where a brief, weak tornado may occur along an already severe line of thunderstorms?
- Should NWS offices simply issue Severe Thunderstorm Warnings with a “Tornado Possible” tag in these type of scenarios as opposed to a full Tornado Warning?
- **Big Picture Question:** In a similar scenario such as this event, where the tornado threat is minimal but not zero, how should NWS offices warn for potential brief spin-up tornadoes along a line that is already producing damaging winds of the same magnitude as a small tornado?
Event #4: July 20, 2018 (Severe Weather Outbreak Across NWS Louisville Area)

On Friday, July 20, 2018, the environment across much of central Kentucky and southern Indiana was primed for a significant severe weather outbreak. The setup resembled that of a typical severe weather event that is common in the area during the Spring months, even though it occurred during the heart of summer. The severe threat was recognized two days in advance, with the SPC issuing a Day 3 Slight Risk (Level 2 out of 5) for severe weather across central Kentucky and southern Indiana.

![Day 3 SPC Convective Outlook](image)

Figure 2.25: Day 3 SPC Convective Outlook, issued July 18, 2018. (Courtesy SPC)

Given the time of year, substantial moisture was available for storms to utilize across this area. Forecasters at the time of the Day 3 Outlook commented that “surface dew points should be in the upper 60s and lower 70s F. In response to surface heating, moderate to strong instability is forecast to develop…Thunderstorm development will be possible along the northern side of the strongest instability from southeast Illinois southeastward into western and central Kentucky Friday afternoon,” (Broyles, 2018).
Confidence in severe weather on Friday had increased enough on Thursday, July 19 that the SPC upgraded the area to an Enhanced Risk (Level 3 out of 5) for severe weather over the same area in the Day 2 Outlook. Upgrades to an Enhanced Risk the day before a severe weather event are not uncommon, but often lead to increased concern over the potential for widespread severe weather with a given event. SPC Forecasters Dean and Dial described this event in their Day 2 Outlook discussion by saying “A potentially significant severe thunderstorm episode is possible across portions of the MS/TN/OH Valleys on Friday,” (2018). The forecast by this point was suggesting several clusters of storms during the morning hours in the areas of greatest concern for severe weather later in the day. On occasion, thunderstorms during the early morning hours could potentially inhibit additional severe weather during the day. However, given the ample amount of moisture from the Gulf of Mexico, dew points near 70 degrees, and high wind speeds and wind shear, the ingredients were still in place for a potentially significant severe weather event.

Early in the morning on July 20, the SPC upgraded much of central Kentucky, southern Indiana, and western Tennessee to a Moderate Risk (Level 4 out of 5) for severe weather. Moderate Risks as well as High Risks (Levels 4 and 5) are the most uncommon levels of severe weather forecast by the SPC but also the most significant and most concerning. This event is the only event in this case study with a Moderate Risk or higher, as these risks are not that common in this study area.
The forecast thoughts were still on track from the last couple of days and the ingredients were still in place for widespread severe weather. The only forecast questions left were when and where the first clusters of severe storms would develop. For NWS Louisville, these questions would be answered around 1:00 PM when a supercell storm developed in southern Indiana. By this time, the supercell was already severe and looked to be developing a hail core as shown in the pink pixel area at the center of the storm.
Figure 2.27: Base Reflectivity at 12:58 PM shows a severe storm in southern Indiana with a hail core developing as indicated by the pink pixels in the center of the storm.

At 1:35 PM, the SPC issued a Tornado Watch for all of NWS Louisville’s coverage area. The prime time for severe weather, including tornado development, was now just beginning. By 1:45 PM, the supercell across southern Indiana was beginning to develop a hook echo, similar to what was observed with the Logan County supercell in Event #1. Rotation was not too strong at this point, but given the environment in place, it was only a matter of time before rotation strong enough to potentially produce a tornado would develop. Indeed, the rotation continued to strengthen and a Tornado Warning was issued for Harrison County, Indiana at 2:00 PM.
Figure 2.28: A Tornado Warning is issued just to the west of Louisville as the supercell begins to develop a hook echo signature seen on ‘classic’ supercells.

The rotation developed rapidly soon after the Tornado Warning was issued and the hook echo signature was very strong, looking eerily similar to ‘classic’ supercells seen on radar with tornadoes across the Great Plains. By 2:12 PM, the hook echo now had a clear ‘ball’ of higher reflectivity, indicative of potential debris being lofted from a tornado. As a result, NWS Louisville upgraded the Tornado Warning to a “Particularly Dangerous Situation,” calling the tornado a “confirmed large and extremely dangerous tornado,” at 2:16 PM. However, unlike the Clarksville tornadoes in Event #2 where the tornadoes were “radar confirmed,” a tornado had indeed been observed by storm spotters. There was no doubt that a tornado was on the ground.

The tornado signature remained quite strong on radar until around 2:25 PM, when the rotation began to weaken rapidly and eventually fall apart, just before the storm crossed into the city of Louisville. NWS Louisville dropped the Tornado Warning at 2:45 PM and downgraded it to a Severe Thunderstorm Warning for the city of Louisville.
itself. The storm moved out of the city by 3:30 PM and no longer posed any tornadic threat. Storm surveys following the event did confirm an EF-1 tornado across southern Harrison County with winds of 105 MPH at its peak. The tornado touched down at 2:04 PM, giving residents a four-minute lead time to take shelter before the initial tornado touchdown. The tornado lifted at 2:20 PM and only resulted in one minor injury.

Considering the rapid development of the rotation with this supercell, the Tornado Warning was timed very effectively with this storm as it moved across Harrison County. Perhaps the most critical component of this warning that made it so successful was that actual storm spotters confirmed a tornado. That is, this was not a “radar confirmed tornado,” but a tornado that was confirmed and actually seen by people with their own eyes. This is opposite the Clarksville tornadoes in Event #2, where NWS Nashville relied on radar data to confirm that the tornado was on the ground despite having no actual in-person confirmation of a tornado touchdown. Having actual storms spotters in the field confirming the tornado established a sense of legitimacy with the phrasing the NWS used in this warning. People actually confirmed to NWS Louisville that a tornado was on the ground, thus legitimizing the usage of the phrase “confirmed large and extremely dangerous tornado,” when the warning was updated at 2:16 PM. While forecasters had a reasonable belief that a tornado was on the ground in Clarksville based on radar imagery and the environment in place that was conducive for tornadoes, you cannot necessarily fully confirm a tornado based on radar alone with no actual confirmation from people seeing a tornado. Radar imagery, most notably the Correlation Coefficient, are very effective at indicating that a tornado is likely on the ground, but do not necessarily
confirm a tornado is on the ground. Only actual observations from people can truly confirm if a tornado is on the ground or not.

The initial cluster of severe storms during the afternoon hours began to push off to the south and east of Louisville toward the Interstate 75 corridor as the evening progressed. However, by 8:00 PM, a new cluster of severe storms was beginning to fire off north of the Ohio River, moving southeast towards Louisville and into Kentucky. This was the main cluster that the SPC forecast could produce widespread wind damage and isolated tornadoes throughout the forecasting of this event. In response, a new Tornado Watch was issued for parts of NWS Louisville’s coverage area from Elizabethtown, Kentucky points southward to the Tennessee state line. All of NWS Nashville’s area was also placed in this watch, but the severe threat did not materialize in that area.

At 9:01 PM, a Tornado Warning was issued for a new supercell in Breckinridge County, Kentucky, ahead of what would eventually develop into a full line of severe storms along the Ohio River. As the supercell moved to the southeast, the rotation was not particularly impressive. But given the ingredients in place as well as the damage from similar storms earlier in the day, NWS Louisville decided to stick with a Tornado Warning out of an abundance of caution. The rotation really tried to tighten around 9:30 PM, but was just not strong enough to warrant a new Tornado Warning to be issued. Thus, a Severe Thunderstorm Warning was issued as a replacement and the tornado threat subsided…for a few moments.
Figure 2.29: Base Reflectivity and Storm Relative Velocity show the rotation with the Breckinridge County storm weakening just before 9:30 PM. The storm was downgraded to a Severe Thunderstorm Warning for a few moments.

By 10:00 PM, the supercell was continuing to struggle to get organized, continuing to keep the tornado threat with it in check. Meanwhile, the broken line of storms along the Ohio River was now beginning to congeal into one line. The straight-line wind damage threat was now beginning to come into focus with this line. Severe Thunderstorm Warnings were now in effect all along this line to account for this damaging wind threat. As for the supercell ahead of the line, Severe Thunderstorm Warnings continued to be issued as the storm continued to move southeastward into Hardin and Grayson Counties. However, by 10:10 PM, the supercell was beginning to reorganize and the rotation was beginning to redevelop. As a result, NWS Louisville issued a second Tornado Warning for this storm, this time for portions of Hardin and Grayson Counties.

While the rotation was continuing to intensify, the overall structure of the supercell was not necessarily the ‘classic’ look commonly seen in most tornado-
producing supercells. Nonetheless, the rotation held together as the storm continued to track southeast, moving towards Hart County, Kentucky.

Figure 2.30: The rotation reintensified, prompting a second Tornado Warning, this time for Hart County, KY. Storm Relative Velocity (right) shows the increased rotation at 10:26 PM.

By 10:30 PM, the rotation had fallen apart once again, as the winds inside the storm had weakened in speed and the wind direction appeared to exhibit more of a straight-line wind threat as opposed to a tornado threat. The Tornado Warning was dropped at 10:45 PM and a new Severe Thunderstorm Warning was issued in its place.
Figure 2.31: The rotation had weakened considerably by 10:40 PM and the warning was once again downgraded to a Severe Thunderstorm Warning for the second time.

As the supercell continued its slow southeast progression, the rotation did not look very impressive on the Storm Relative Velocity radar product. However, the Normalized Rotation product indicated that there was still sufficient rotation within the storm that a brief tornado could touch down. At 10:54 PM, NROT values were in the 1.00-1.50 range, sufficient for possible tornadic development. At 10:59 PM, a third Tornado Warning was issued for this storm to include Hart County. This was a short term warning, only lasting until 11:15 PM, similar the brief Tornado Warning issued for the city of Louisville analyzed in Event #3 of this case study.
The rotation with the supercell had yet again increased in intensity at 11:00 PM, arguably at its strongest of its entire life cycle. The rotation was particularly tight as it crossed Interstate 65 between Bonnieville and Munfordville in Hart County. But just as quickly as the rotation had intensified, it collapsed as it continued southeast across Hart County. By the time the Tornado Warning expired at 11:15 PM, the rotation had weakened enough to where a tornado was no longer a threat.
Figure 2.33: While rotation was still present, the Tornado Warning was downgraded to a Severe Thunderstorm Warning for the third time in this storm’s life cycle.

Yet another Severe Thunderstorm Warning replaced the expiring Tornado Warning. The supercell would begin to lose its strength after this as the line of storms behind it had caught up to the supercell and was starting to ‘steal’ its energy and moisture. By midnight, the supercell had lost any characteristics indicative of tornado development and had become nothing more than a heavy thunderstorm. Storm surveys following the event concluded that a brief EF-1 tornado with 90 to 95 MPH winds touched down in northwestern Hart County at 10:56 PM, three minutes before the third Tornado Warning was issued for that storm. Despite the three total Tornado Warnings with this storm, there were no other tornado touchdowns observed on its path.

I had the opportunity to work at the NWS Louisville office as this event unfolded. As one would expect, it was very busy around the office. Many forecasters who were not scheduled to be on shift at the time either stayed late or came in on an off day. With regards to this specific supercell, however, I remember the forecaster overseeing the
warnings on this storm having an internal battle trying to decide their plan of attack with issuing warnings as the storm progressed. Should they stick with a Severe Thunderstorm Warning or upgrade to a Tornado Warning? The forecaster inquired with several other forecasters and myself that were on shift, seeking any input on what to do with issuing the next set of warnings for the storm. What was clear throughout the entire duration of the storm was that it was clearly at or above severe criteria (58 MPH winds and/or quarter sized hail). Therefore, at minimum, there would always be at least a Severe Thunderstorm Warning on the storm until it weakened. But the rotation with the storm was up for debate. At times, it would pulse up just enough to where a forecaster could reasonably issue a Tornado Warning. Other times, the rotation was still present, but did not necessarily pose an immediate threat to producing a tornado. This debate over the rotation in the storm and its ‘pulsing’ nature is the reason that the warnings alternated back and forth between Severe Thunderstorm and Tornado Warnings.

From a scientific standpoint, this alternating of warnings was correct. If the rotation was not strong enough to potentially produce a tornado, then there is no need for a Tornado Warning. However, in the eyes of the public, this alternating may come off as NWS forecasters being undecided and perhaps unsure of what to really do with the storm in question. This could be especially true if the alternating warnings are short-duration warnings (i.e., 20 minutes or less). This could lead to distrust among some people in the public, possibly leading to inaction in taking shelter from a severe storm, which could lead to serious injury or worse in the more extreme scenarios. Here are a few questions based on this theory to take away from this event in this case study.
• How do the people in the area that you forecast feel about alternating between Severe Thunderstorm and Tornado Warnings with a single storm? Do they see that as indecisiveness?

• Does the public react differently with regards to taking shelter when the warning type changes back and forth such as in this scenario?

• From a warning perspective, in a scenario with a ‘pulsing’ rotation such as in this event, is it just as well to stick with a Severe Thunderstorm Warning with a “Tornado Possible” tag?

• **Big Picture Question:** In scenarios where rotation has been consistent in a storm but has been ‘pulsing’ in strength and intensity, how should forecasters issue warnings with the storm in order to avoid alternating between Severe Thunderstorm and Tornado Warnings?
Event #5: September 24, 2018 (Unwarned Tornado in Cannon County, Tennessee)

The severe weather potential on Monday, September 24, 2018 was very minimal across middle Tennessee. So much so that the SPC had no severe weather outlook of any kind for the area. In their Day 1 Convective Outlook issued the morning of the 24th, the forecasters noted that, “The overall scenario appears to be quite marginal, such that severe…probabilities are too low to warrant an outlook area,” (Thompson/Nauslar, 2018). Locally, the forecast for middle Tennessee was more like a typical summer day, with clouds and a chance for a few pop up thunderstorms with daytime heating in the afternoon. No severe threat was really on the table.

Just after 4:00 PM that afternoon, a few of these stronger thunderstorms were beginning to make their way through counties east of Nashville, notably Cannon and DeKalb Counties. These storms seemed pretty benign in nature until around 4:11 PM when two small isolated storms began to exhibit some rotation, as seen on Storm Relative Velocity in Figure 2.34. Normalized Rotation was also showing values between 0.50 and 1.00, suggesting some rotation present, but not strong enough at the moment to cause any serious concerns.
Figure 2.34: Base Reflectivity and Storm Relative Velocity show two stronger storms with some weak yet broad rotation between Beechgrove and Woodbury, TN at 4:11 PM.

At 4:19 PM, Storm Relative Velocity showed a very tight couplet of green and red pixels to the west of Woodbury, Tennessee in Cannon County. In a typical severe weather scenario, this would likely be enough to issue a Tornado Warning, but with such a low severe threat in place, no warning was issued.
This initial tight rotation west of Woodbury would weaken and the storm would recycle, producing a new yet weaker rotation as it passed through Woodbury just after 4:30 PM. As this storm was beginning to recycle and weaken once more, a storm to the north moving into DeKalb County was beginning to show rotation to the south of Liberty, Tennessee. I was at the office as this event began to unfold. I recall this rotation catching the attention of the NWS forecasters as the circulation stayed relatively strong moving northeastward into DeKalb County. NWS Nashville issued a Tornado Warning for this storm at 4:53 PM.
Figure 2.36: NWS Nashville issued a Tornado Warning for DeKalb County for broad rotation near Liberty, TN at 4:53 PM.

However, almost as soon as the warning was issued, the rotation weakened considerably. NWS Nashville kept the warning in place as the rotation was still present, but was in a weaker state than it was just a few minutes earlier. By 5:20 PM, any rotation that was left had dissipated. The warning was cancelled at 5:19 PM.

There were no damage reports of any kind from the storm that prompted the Tornado Warning for DeKalb County. However, just after that warning was issued, the office received a call from the public of possible tornado damage near the community of Bradyville. None of the forecasters knew where Bradyville was located. They tasked me with searching for this community. My results indicated that it was located in western Cannon County, very close to where the tight red and green pixels were spotted on radar around 4:20 PM that afternoon. After going back and looking at radar data, I discovered the rotation to the west of Woodbury in western Cannon County around 4:20 PM that
afternoon. That rotation was the tight red and green pixels close together at 4:19 PM as seen in Figure 2.35. All the forecasters, as well as myself, had failed to notice the circulation, meaning the tornado went unwarned. A storm survey concluded that a weak EF-0 tornado had touched down near Bradyville, resulting in tree damage, minor roof damage to two homes, and a destroyed barn. There was no tornado with the warned storm that moved through DeKalb County.

It is difficult to assess the effectiveness of the warning process with this event. While the chance was there for a storm to ‘go rogue’ and become severe for a brief period, the environment did not seem conducive for anything more than some brief damaging winds. The main point of consideration is whether or not the forecasters on duty perhaps had their guard down for this event because there was little evidence to support the development of severe storms. With events that are forecast well in advanced, meteorologists prepare their minds for the potential of severe weather so that they are mentally ready for anything that may happen. However, in this case, a severe weather mindset was not in place because there was no reason for it to be until the storms began to rotate. The question going forward is how to better prepare for ‘random events’ such as this one and whether or not a forecaster’s mindset affects the way they issue warnings.

- How do forecasters respond to severe weather events when they are not expected to occur?
- Does the mindset of forecasters affect the accuracy of warnings in severe weather events that were well-forecast compared to events that were ‘unexpected’?
- **Big Picture Question:** What steps need to be taken, both in forecasters mindsets and the warning process, to ensure that the accuracy of warnings
issued is unaffected by whether or not the event was ‘expected’ or ‘unexpected’?

Event #6: November 5, 2018 (Deadly Tornado in Christiana, Tennessee)
The sixth and final event of this case study focuses on the most widespread severe weather to take place in either the NWS Louisville or NWS Nashville coverage areas in 2018. Like most of the events in this case study, the potential for severe weather on Monday, November 5 was forecast several days in advance. The SPC had issued a Day 4, 30 percent risk of severe weather mainly across Mississippi, Louisiana, eastern Arkansas, and southwest Tennessee. A Day 4 severe risk is not uncommon, but a 30 percent risk for severe weather on Day 4 is something that garners a forecaster’s attention. By Day 3, the area of greatest concern and the threats in play were starting to come into focus. An Enhanced Risk (Level 3 out of 5) was posted for western Tennessee, extreme southern Kentucky, northern Mississippi, northern Alabama, and eastern Arkansas. Forecasters at the time saw the potential for “significant severe weather to transpire Monday evening and overnight, mainly from the Lower MS Valley into the TN Valley regions,” (Dial, 2018). Sufficient moisture in the lower levels of the atmosphere combined with strong wind shear in the upper levels would provide just enough energy to produce a widespread severe weather event Monday evening across primarily middle Tennessee.

The forecast thinking remained consistent from the SPC up until the day of the event. Storms would likely start off as discrete, isolated supercells during the afternoon across Louisiana and Arkansas, which is where the greatest wind shear was located. The forecast would be for these supercells to then congeal into a line that would race across Tennessee during the evening and into the overnight hours. Fast wind speeds aloft combined with enough instability resultant from dew point values in the 60s and sufficient wind shear aloft would pose the threat for damaging straight-line winds and a few spin-up tornadoes along the line as it crossed through Tennessee. Should the storms
become a cluster as opposed to an organized line, some of the tornadoes that developed could be strong.

During the early evening hours, a large swath of heavy rain soaked areas north of Interstate 40 in middle Tennessee, from mainly Nashville points north. This limited much of the severe weather north of Nashville to the line of storms that would pass through later in the evening. Nonetheless, NWS Louisville surveys following the event concluded that three tornadoes occurred in its coverage area, including one in Edmonson County about 20 minutes north of Bowling Green. However, the main epicenter of severe weather would be centered in NWS Nashville’s coverage area as an untapped environment south of Nashville was still primed for severe weather as the line of storms began to race into middle Tennessee.

Just before 10:00 PM that evening, NWS Nashville surprisingly had no warnings of any kind in effect for any part of their area. However, the line of storms was still broken apart and was just beginning to move into the area of greatest instability and wind shear. The first of what would prove to be many Tornado Warnings that evening was issued for the northern suburbs of Nashville at 9:55 PM. The circulation remained relatively weak until around 10:22 PM, when a Tornado Vortex Signature was detected on radar.
Although the rotation was not particularly impressive, NWS Nashville reissued the Tornado Warning further east as a precaution. As this northern rotation continued eastward, more problems were beginning to develop southwest of Nashville. As the line began to come together and enter the area of greatest instability and shear, embedded areas of rotation developed along the line of storms near the Alabama border. Within a three-minute span from 10:31 to 10:34 PM, five counties along the Alabama line went under Tornado Warnings. The severe weather outbreak was getting underway.

Over the next 20-30 minutes, the rotations embedded in the line were strong enough to warrant Tornado Warnings especially given the environmental conditions, but were still unimpressive with regards to possible tornadoes on the ground. New Tornado Warnings were issued at 10:55 PM further northeastward as the line continued to progress towards Interstate 65. Concerns increased quickly around 11:15 PM, when the
Correlation Coefficient picked up a minimum collocated with the rotation near Duck River, Tennessee along the Maury-Hickman County line. NWS Nashville promptly issued a new Tornado Warning, calling the circulation a “radar confirmed tornado,” based on what was observed on the Correlation Coefficient.

Figure 2.38: Correlation Coefficient at 11:15 PM suggested debris being lofted from another circulation along the line southwest of Nashville. However, the rotation still looked very weak on radar.

What was peculiar about this Correlation Coefficient minimum was that the rotation did not appear too impressive on Storm Relative Velocity. That is, the storm did not really appear as though it was producing a tornado based on the actual velocity products. Nonetheless, the Tornado Warnings continued.

More Tornado Warnings would continue to be issued both across the southern part of the state near the Alabama border and further eastward with the radar confirmed tornado which was now in Williamson County. However, by midnight Tuesday morning, the line seemed to be weakening and perhaps transitioning into more of a damaging wind threat as opposed to a tornado threat. NWS Nashville began issuing Severe Thunderstorm
Warnings along the Interstate 24 corridor in response. However, the rotations embedded within the line would begin to reform and new Tornado Warnings followed in their wake. The rotation that was reported as a radar confirmed tornado an hour or so earlier in Hickman County had reorganized as it crossed into Rutherford County, approaching the community of Smyrna. Correlation Coefficient was also picking up on a minimum in the same area as the rotation, perhaps indicating debris being lofted.

Figure 2.39: Correlation Coefficient depicting a minimum collocated with an area of rotation in northern Rutherford County, TN at Midnight.

**The Christiana Tornado**

Just to the south of this tornadic circulation in northern Rutherford County, a new Tornado Warning had just been issued, encompassing the rest of Rutherford County. The rotation was broad and weak, but still enough to potentially produce a brief, spin-up tornado. At 12:16 AM, however, it was clear that a tornado was in its beginning stages across western Rutherford County. The rotation had become considerably stronger over the last 15 minutes and a Correlation Coefficient minimum was collocated with the
rotation right over the community of Rover, Tennessee. NWS Nashville promptly issued a new Tornado Warning at 12:23 AM, calling the rotation approaching Christiana “a tornado producing storm.”

Figure 2.40: A strong Correlation Coefficient minimum collocated with an area of strong rotation on Storm Relative Velocity approaching Christiana, TN at 12:23 AM.

At 12:28 AM, the debris signature was located directly over Christiana, with a signature on Storm Relative Velocity that was the strongest rotation seen throughout the entire night. NWS Nashville upgraded their warning at this time to a “Particularly Dangerous Situation” for Christiana and the city of Murfreesboro.
Figure 2.41: Storm Relative Velocity and Correlation Coefficient moments after the tornado went through Christiana.

As the tornado approached Interstate 24, the signature on Storm Relative Velocity did not appear as strong as it did a few scans earlier. However, Correlation Coefficient continued to suggest that debris was still in the sky from where the tornado had touched down earlier. As the rotation that resulted in the Christiana tornado weakened, a new rotation appeared to be forming. At 12:49 AM, a strong rotation near Auburntown in Cannon County had resulted in a Tornado Vortex Signature being detected on radar. NWS Nashville once again issued a new Tornado Warning with a confirmed tornado near Auburntown at 12:53 AM.
Figure 2.42: Tornado Vortex Signature near Auburntown, TN at 12:49 AM, as seen on Storm Relative Velocity and Correlation Coefficient.

Just one minute later, radar imagery showed a clear rotation signature just to the east of Auburntown collocated with a strong Correlation Coefficient minimum. Debris was being lofted from what was likely another tornado. This tornado would continue to move northeastward into DeKalb County before weakening and eventually lifting around 1:00 AM. Although one or two additional Tornado Warnings were issued downstate, the worst of the tornado outbreak was over.
NWS Nashville confirmed a total of nine tornadoes across its coverage area on November 5 and the early morning hours of November 6. Of those nine tornadoes was an EF-0 tornado in Hickman with the first radar confirmed tornado around 11:10 PM that evening. In addition, an EF-1 tornado with winds of 95 MPH occurred in Cannon and DeKalb Counties between Auburntown and Liberty, touching down at 12:50 AM. The Christiana tornado that is the focus of this case study event produced an EF-2 tornado with winds of 135 MPH, touching down at 12:16 AM. This tornado lifted a large, newly built brick home off its foundation and flipped it over as it remained almost fully intact (NWS Nashville, 2018). One woman inside the home was killed. It was determined that the house was not well-attached to its foundation, a construction error that significantly contributed to the house being lifted off its foundation. The tornado warned storms that crossed through the northern suburbs of Nashville early in the evening did not produce a tornado. No tornado evidence was discovered in Williamson County either, an area where
forecasters had said a radar confirmed tornado was on the ground just after 11:00 PM that evening based on the Correlation Coefficient product.

Although I was not working at NWS Nashville as the event itself took place in the evening, I did have the opportunity to work the day shift leading into the event. The atmosphere around the office was very calm and very focused. Towards the end of the shift, I remember all the forecasters on shift during the day as well as the new forecasters coming in for the evening shift getting together to lay out a strategy for handling warnings with this event. Man power resources were discussed should extra help be needed for a widespread event. I saw first-hand the amount of preparation, coordination, and strategy necessary at a NWS office to prepare for a large-scale severe weather such as what took place on November 5. Given the broad coverage area of a NWS office, as well as the potential for this event to become widespread, this level of coordination, preparation, and cooperation is vital among NWS forecasters as well the meteorology industry as a whole to ensure an effective warning process. This preparation and coordination allows NWS forecasters to issue timely, accurate warnings, which is then relayed through television meteorologists who can quickly disseminate information to the public so that they can take proper safety precautions.

In the case of November 5, the warning process worked extremely well. Of the nine tornadoes that occurred across the NWS Nashville area, eight of them had a Tornado Warning in effect at the time of initial touchdown. For the ninth tornado, a Tornado Warning was issued just one minute after the tornado touched down in White County. Despite the loss of life in the Chirstiana tornado, NWS Nashville provided plenty of lead time in the Tornado Warnings issued on November 5, allowing the public ample
opportunity to seek shelter before the tornadoes touched down. The adequate lead time and accurate warnings associated with this event merits recognition considering the difficulties of detecting tornadoes along a line of severe storms. Perhaps one drawback with the accuracy of warnings issued in a widespread tornado outbreak such as with the November 5 event is too many warnings being issued in the same location at the same time. In Rutherford County as the EF-2 tornado was striking the community of Christiana, there were five different simultaneous severe weather warnings in effect for different parts of the county: two Tornado Warnings, a third Tornado Warning for the confirmed Christiana tornado, and two Severe Thunderstorm Warnings. The city of Murfreesboro itself was under four of these five warnings at one time. While some of these warnings were outdated and about to expire, all of these warnings were relayed directly to the public via NOAA weather radios and/or television coverage. Therefore, residents of Rutherford County heard five separate warnings for their area in the same time period. This can cause confusion among the public if they hear numerous warnings issued in a short time period, especially if the warnings have different labels (i.e., Severe Thunderstorm or Tornado). While issuing multiple warnings may be scientifically correct in a given situation, it may not necessarily be the best way to clearly communicate the threats to the public.

- Do multiple warnings in effect for the same area at one time confuse members of the public?

- In these widespread severe weather events, should NWS forecasters be more mindful of cancelling outdated warnings to avoid confusion if new warnings are issued for the same area?
• With multiple rotations over the same area at one time, should NWS forecasters consider issuing one larger ‘blanket’ warning to cover all rotations instead of multiple smaller warnings?

• **Big Picture Question:** How can NWS forecasters issue better warnings in scenarios with multiple threats in the same general area without causing confusion amongst the public with multiple warnings in effect for the same area at the same time?
CHAPTER THREE

DISCUSSION

The six events used in this case study provided a variety of severe weather events in our region that can serve to evaluate the effectiveness of the severe weather warning process. With each of these events, the success and effectiveness of the warning process also varied, depending on the type of event taking place. As a whole, the warning process was effective in issuing scientifically accurate and timely warnings with each of the severe weather events analyzed in this case study. With most events, the warning process successfully achieved its goal: protecting life and property during times of severe weather. The lone exception would be the Logan County supercell analyzed in Event #1, where an elderly woman was killed by the tornado before a warning was issued. As discussed in Chapter One, NWS forecasters can only do so much in issuing timely and accurate severe weather warnings. Heeding those warnings is dependent on the public. Therefore, it is perhaps unreasonable to assign blame for injuries and/or fatalities in severe weather events on the warning process if warnings are issued in advance of the severe weather. In some extreme cases, even taking substantial shelter during severe weather may not be enough to protect your life, as seen with the loss of life with the Christiana, Tennessee tornado in Event #6.
While the warning process still remains largely effective in its goal to protect the public, there are still some notable factors found in this case study that could be addressed to improve the process for the future. When analyzing the effectiveness of the severe weather warning process, it is important to remember that there is more to the process than simply issuing warnings in advance of severe storms to protect those in harm’s way. There are many factors considered when issuing these warnings and ultimately determining whether or not the warning process was truly effective in the mission of protecting life and property. While there are quantitative metrics that can be used to assess the warning process, such as the FAR and lead time, there is no distinct metric that analyzes the overall effectiveness of individual severe weather warnings. Therefore, we must rely heavily on qualitative analyses such as in this case study to give the meteorological community a better perspective on what can be improved upon with the warning process in the future.

In addition to adding my personal experiences, these events highlight different components of the warning process where improvement might be desirable and/or possible. Each of these components are summarized using the “Big Picture Questions” bullets at the end of each case study event and serve to spur conversation in the meteorological industry for enhancing the warning process. These topics could include better coordination between neighboring offices in issuing warnings as severe storms cross CWA boundaries; issuing warnings when data suggests that a tornado is likely on the ground even though a tornado has not been visually confirmed; and how to properly
issue warnings in scenarios where a tornado is present, but still quite low. Additional topics based on these case studies include how to avoid alternating the two severe weather warning types during the life cycle of a storm, accurately issuing warnings whether an event is expected or unexpected, and whether or not it is better to issue a ‘blanket’ warning for a given area instead of multiple different warnings with different labels at the same time.

At first, these “Big Picture” topics might seem like small details in the grand scheme of severe weather events as a whole. However, these small details can make all the difference in whether or not the public will actually take action when severe weather is threatening. For example, consider the July 20 event which involved the supercell across central Kentucky with alternating Severe Thunderstorm and Tornado Warnings. In a hypothetical scenario, consider a member of the public who saw this storm approaching their area. They notice that the warnings on the storm continue alternating between Severe Thunderstorm and Tornado Warnings. Perhaps the public subscribes to the “cry wolf” syndrome, believing the NWS issues too many Tornado Warnings where nothing ever happens. As a result, the public is skeptical about the warning process and decides it is not necessary to seek shelter. Although hypothetical, this is the unfortunate reality that the meteorological community must deal with on a far too common basis. In any scenario, it is always important to ensure that the public is actively engaged in any severe weather that is imminent or occurring. Because of this, it is critical that forecasters address any details in the warning process that could perhaps be improved upon in the
future, no matter how small the detail might be. While we will never be able to fully perfect the severe weather warning process, any improvements that can be made in the future will further boost the scientific accuracy of the process, but also enhance the credibility of our profession in the eyes of the public. Through this enhanced accuracy and credibility, lives can be saved.
The severe weather warning system operated by the National Weather Service has proven to effectively protect life and property for many years. The scientific accuracy of the warning process in the United States is arguably the most sophisticated and effective system in the world. However, this case study showing six severe weather events during 2018 demonstrates that there are still flaws in the warning process that should be addressed to improve the system for the future. These ‘big picture’ flaws include the handling of severe weather warnings as a storm crosses between two neighboring NWS office CWAs; the real definition of a “radar confirmed tornado” and whether or not this is a viable definition that should be used when issuing Tornado Warnings; and how NWS offices should issue warnings for events where the tornado threat is there, but minimal. Additional ‘big picture’ flaws to consider are how to avoid alternating between Severe Thunderstorm and Tornado Warnings on a single storm; ensuring the accuracy between ‘expected’ and ‘unexpected’ severe weather events remain relatively the same; and whether or not multiple warnings within a small area at one time are confusing to the public and how to properly warn for multiple threats over a single area at one time.

It is important to note that the purpose of this case study is not to diminish the warning process nor degrade the forecasters across the NWS who work tirelessly to keep
American citizens safe from severe weather year-round. Instead, this case study is designed to spark conversation about how the meteorology industry can address potential issues in the warning process. Future research should focus on specifically analyzing additional occurrences of the six ‘big picture’ flaws discussed in this case study. These flaws could also be analyzed in a different spatial context, perhaps on a national scale to validate their existence, frequency, and impact. Research could also investigate when these flaws in the warning process present themselves throughout the year; trends in time of day; or additional human factors such as the experience of the forecaster. It is also important to seek additional public opinion on the warning process. Further research should seek public input on what they understand about the process, what components do they have trouble understanding, what actions they take during severe weather events, and how effective they feel the warning process is as a whole.

It is imperative that this future research on the warning process, its flaws, and public opinion be conducted before addressing how to resolve the issues with the warning process discussed in this case study. It is also important to ensure that all sectors of the meteorology enterprise provide input into this discussion and how they feel the warning process could be improved. These sectors may include broadcast television meteorologists, private sector forecasting firms, scientists and academicians, and emergency management agencies in addition to National Weather Service forecasters. Once the meteorology community has a greater understanding of the warning process and its limitations, combined with input from the industry and the public, the various groups
can work together to find new, innovative ways to not only address concerns with the current warning process, but also perhaps create a new warning process that enhances scientific accuracy as well as public trust. While we will never have a perfect warning process, nor will all of the public ever be fully engaged in severe weather awareness and response, any improvements made in the warning process will prove to be more effective in protecting the lives and property of the people that meteorologists serve on a daily basis.
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