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The Tri-State and Quad-State Tornado Systems: A Comparative Case Study

Brittany Hodge
Atmospheric Sciences
The University of North Carolina Asheville
One University Heights
Asheville North Carolina 28804 USA

Faculty Advisor: Dr. Christopher Godfrey

Abstract

On the night of 10 December 2021, a storm system ravaged the Southern United States and Ohio Valley with a series of historically damaging tornadoes, including two long-track tornadoes that, combined, traveled an astonishing 257 miles across four states. It did not take long for many to make a comparison between this storm and the record setting Tri-State Tornado system of 1925. In this comparative case study, synoptic and mesoscale data are compiled to determine the similarities between the two systems. In the days following the December disaster, damage assessments confirmed that the long-track tornado that led to the initial comparison was actually a series of five tornadoes, three of which were noticeably short and of low intensity. While this revelation may lead one to dismiss any further comparisons, recent studies discussed within this research paper suggest that this same situation may also have occurred in the 1925 system. Further similarities include the fact that both storm systems occurred in years with abnormally warm and humid winters, as well as strong evidence that a deepening upper-level trough led to surface conditions favorable for such tornadic storm systems. A comparison of observations from the 2021 system and recent reviews of the 1925 system leads to the conclusion that these storms were remarkably similar, despite several key differences discussed here.

1. Introduction

On 18 March 1925, a tornadic storm raged through the Midwest United States that left devastation along a nearly straight 219-mile path leaving nearly 700 people dead and several thousand injured or homeless. To this day this tornado, which was later named the Tri-State Tornado, holds records for pathlength and fatalities and it seemed unlikely we would see its equal. That is, until the night of 10 December 2021 in which it was initially believed that a single long-track tornado had traveled a distance of 257 miles along an eerily similar path. It took mere hours for comparisons to be made between the two systems and it seemed as though the Midwest was experiencing the storm that would top the Tri-State's destruction. Dubbed the Quad-State Tornado due to its likeness to its predecessor, the 2021 system spawned numerous tornadoes, one of which caught the attention of the community given its strength and longevity. Initial observations led many to believe that the Quad-State Tornado would outstrip the Tri-State Tornado for pathlength. However, observations by officials in the following days made it evident that the path was made up of several tornadoes. While two were long-track tornadoes, neither surpassed the reigning champion from 1925 for distance.

Despite this, comparisons continue to be made. The goal of this case study is to compare the synoptic and mesoscale events that led to and initiated each system and determine their similarities. There are some significant limitations to work through while reviewing the Tri-State Tornado, given that nearly 100 years have passed since the storm occurred and the fact that upper air observations were unavailable at the time. Simulations by Becker et al.[1] fill in missing data to allow a comparison between these events to be made. Henry[5] discussed the observable surface weather phenomena that occurred leading up to the Tri-State Tornado, as well as the immediate results of the terrible event. More recent

observations will be explored, including those by Chagnon and Semonin[4] and Maddox et al.[7], which detail the large-scale weather phenomena that led to the massively damaging tornado. Chagnon and Semonin[4] examined the surface level observations made by meteorologists and the Weather Bureau in 1925 to recreate the original surface level maps with finer detail, while utilizing models developed by the 1960s to produce maps of the most likely synoptic conditions that led to the parent supercell of the Tri-State Tornado. Maddox et al.[7] re-examined the limited research that had been done in regard to the Tri-State Tornado, including Chagnon and Semonin's[4] work, and sought to provide a corrected and more thorough evaluation of the synoptic events leading to the Tri-State tornado. Careful analysis of multiple inconsistencies in the recorded observations of 1925 and the reports that came after gave reason for newer models to be utilized to provide the community with a better understanding of the rather mundane conditions from which the long-track tornado spawned. These findings give way to continued research into just why long-track tornadoes do not spawn more frequently. Thankfully, the Quad-State Tornadoes were able to be studied *in situ* utilizing modern observational technology, as well as numerous maps and discussions from the NOAA Storm Prediction Center (SPC) and NOAA National Centers for Environmental Prediction (NCEP).

This paper will begin by discussing the environment leading to each long-track tornado, with an evaluation of the synoptic and mesoscale features of each system. An evaluation of the differences and similarities between each storm will lead to conclusions that will help meteorologists to recognize patterns that are apparent prior to these long-track tornadoes.

2. Data Collection and Methodology

2.1 Tri-State Tornado

The Tri-State Tornado occurred on 18 March 1925, in a time where modern meteorology was still in its infancy. There were relatively few scattered weather stations across the U.S. available to collect data, and upper air observations were completed by plane or by releasing the occasional weather balloon, which were expensive rubber balloons with no means of transmitting data to the station while aloft. Consequently, this meant meteorologists had to hope they found the instruments when they landed so as to obtain the collected data. There were observations collected by utilizing kites during the Tri-State Tornado and those findings have been used in previous research to determine weather conditions at higher elevations during the event, however using only surface observations can lead to some inaccurate figures when trying to model synoptic scale situations.

The Tri-State Tornado was a record setting tornado that would have been rated an EF5 utilizing today's system. It obliterated entire communities through northeastern Missouri, southern Illinois, and southern Indiana, and remains the deadliest in U.S. history having caused the deaths of 695 people and injuring 2027 others. It also holds the record for longest single tornado track in U.S. history at 219 miles traveled over a three and a half hour time period. The tornado traveled at 73 mph at top speed with wind speeds estimated at over 261 mph. Figure 1 depicts the nearly straight-line continuous path of the Tri-State tornado by marking each damage point along said path, allowing the viewer to visualize just how far the tornado traveled.

Figure 1. Image depicting recorded damage points along Tri-State Tornado's path on 18 March 1925.[6]

2.1.1 synoptic environment

The underdeveloped observational capabilities of meteorologists in 1925 caused limitations to the further understanding of the evolving synoptic weather pattern during the Tri-State Tornado. This storm also passed through an area that was void of surface observations, which led to further difficulties in analysis of the system[7]. However, meteorologists today can make reasonable assumptions based on modern day satellite observations, as well as models and simulations (Figures 2 through 4) that have been created in the years since the Tri-State Tornado occurred.

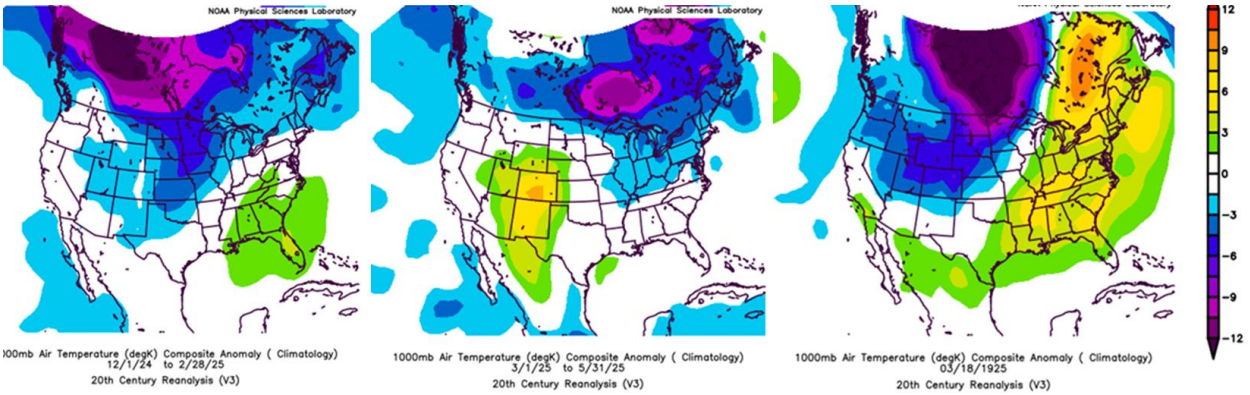

Figure 2. Temperature anomaly maps for 1925 created by NOAA PSL models depicting abnormal temperatures in the winter (left), the spring (center), and the month of the March 1925 tornado (right).

The Tri-State Tornado occurred in a year when the late winter and early spring for the area was atypically warm and dry, however the mean temperatures observed during the spring were cooler than predicted, as depicted by temperature anomaly maps created by NOAA's PSL in Figure 2. March itself was five to six degrees Celsius warmer than climatological assessment would have had meteorologists expect, also noted in Figure 2's right side image. According to a decade-long research project by Maddox et al.[7], a mean ridge would have developed along the west coast alongside a broad central trough. It is likely that a shortwave trough in the mid- to upper troposphere moved over and across the ridge before descending southeastward. A surface low pressure system with cyclonic circulation would have developed over Montana, moving southeast through Colorado and into north Texas before recurving towards the northeast[7]. Figures 3 and 4 demonstrate the movement of the developing line of supercells associated with the storm system leading up to the tornadic event utilizing radar reflectivity models. Evaluating the movement of the pressure system led Maddox and his team to the conclusion that it was a cut-off low moving along a sharp trough and the resultant storm system also suggested a warm, moist tongue of air moving poleward from the south. These conditions are typical precursors of tornadoes[4].

By 0700 CST 18 March 1925, a surface low around 1003 hPa had developed in northeastern Oklahoma, trailed by a cold front which reached southwestward from the low behind a dryline as depicted in Figure 5. At the same time, a warm front reached out from the east. To the north, a complicated mix of mid-level troughs and moist air led to a situation involving strong thunderstorms and heavy rain. At around 1200 CST the low deepened and moved into a "data void" over southern Missouri[7]. However, the information that was obtained outside of this area allows modern day meteorological models to recreate reasonable scenarios for synoptic events that may have occurred during that time period. Figures 5 and 6 are images created utilizing a simulation model with initial conditions input from the *in-situ* observations collected in 1925. The creators of these images note that while the dominant storm developed too quickly using this simulation model, the path it took and the motions along the surface were incredibly similar to those that were observed during the actual Tri-State Tornado[1].

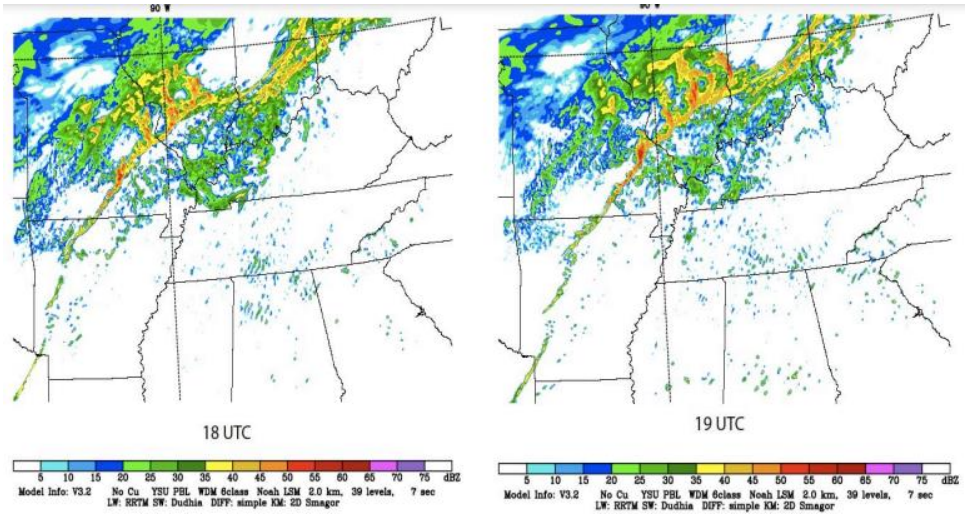

Figure 3. Simulated radar reflectivity images of the Tri-State Tornado storm system at 1200 and 1300 CST 18 March 1925.[1]

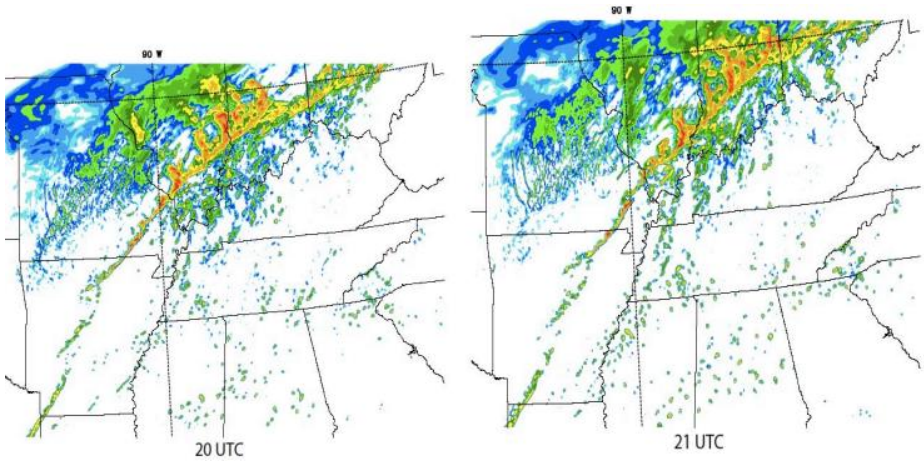

Figure 4. Simulated radar reflectivity images of the Tri-State Tornado storm system at 1400 and 1500 CST 18 March 1925.[1]

The dryline ahead of the Pacific cold front, moving southward from the Northern Plains, also connected to a warm front moving northward. This led to rain-cooled air feeding into the development of thunderstorms from Kansas through to Kentucky and Indiana[7], including the supercell which spawned the Tri-State Tornado. Subsequently, the Tri-State Tornado formed at this triple-point where the cold and warm fronts intersected with the dry line ahead of its associated low pressure system[7]. This particular scenario is incredibly striking given how unusual it is for a dryline to extend so far east of Oklahoma, and likely contributed to the intensity and longevity of the Tri-State Tornado. At 1400 CST, the center of the low-pressure system was situated to the left of the primary tornado and the storm proved to be moving approximately 11 mph faster than the low at this point, leaving the supercell positioned within the warm front's baroclinic zone. This was an advantageous area for the supercell to be located as strong lift and potential for vertical shear are often noted in a baroclinic zone, conditions that are necessary for such strong tornadic events to occur. By 1600 CST, the surface low had deepened to 998 hPa over Illinois while the parent supercell remained nestled in the baroclinic zone, an area visible in Figure 7 which demonstrates the intensity of the temperature gradients in the area, moving further from the low as the afternoon progressed[7]. The pressure decreased to 982 hPa by the time the Tri-State tornado dissipated[4] and strong pressure gradients remained evident from the morning of the eighteenth through to the morning of the nineteenth[7].

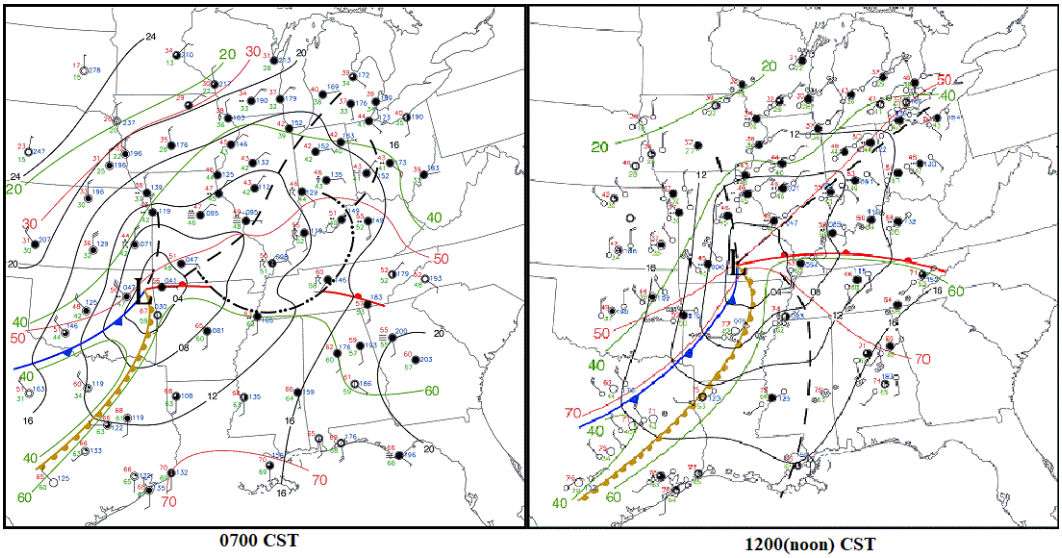

Figure 5. Reanalyzed surface charts for 0700 and 1200 CST 18 March 1925.[7]

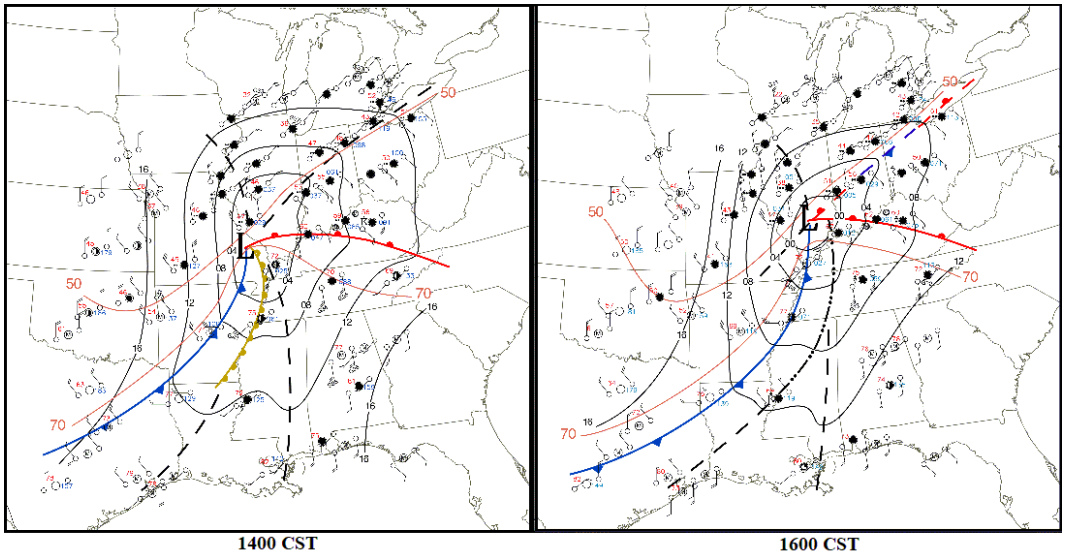

Figure 6. Reanalyzed surface charts for 1400 and 1600 CST 18 March 1925.[7]

2.1.2 mesoscale environment

Once again, there are limitations presented when it comes to access to observations leading up to the Tri-State Tornado event, as there was no mesoscale meteorological network set up in 1925. However, the *in-situ* observations that were collected at the time allow researchers today to make a reliable reconstruction of the weather conditions that were experienced[4].

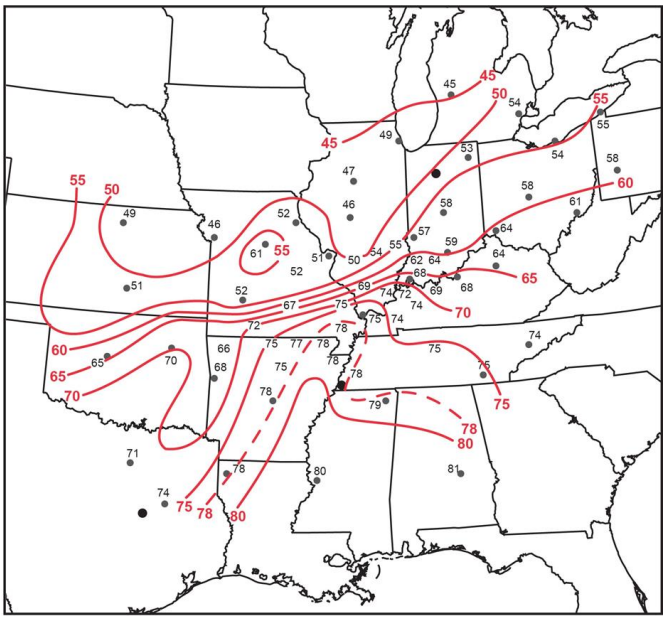

Figure 7. Map depicting strong temperature gradient utilizing maximum temperatures reached on 18 March 1925 indicating intense baroclinic zone.[7]

By 0800 CST, barograph traces had been obtained, and elevated thunderstorms were active in the Northern Great Plains. Light rain had initiated by 1200 CST in Tennessee[7], hail was noted in some scattered areas, while a steep temperature gradient was noted along the future tornado path that afternoon (Figure 7). However, the rain did not precede the tornado which indicated that the tornado was in front of the low-pressure system it stemmed from. At 1300 CST, the Tri-State Tornado spun up near Ellington, Missouri. The funnel was visible from this point and through Annapolis, Missouri. By the time the tornado had reached Biehle, Missouri at 1400 CST there was no discernable funnel[4]. Surface winds around 66 mph and hail were reported as the tornado neared the Mississippi River and moved toward the northeast at 59 mph. By this point the rain-cooled air had slowed the northward movement of the warm front, thus maintaining the strong temperature gradient present at that time. At 1500 CST the winds shifted to the southwest, then by 1600 CST the pressures began to rise as the temperature dropped rapidly[7]. It was shortly after this point that the tornado dissipated just south of Louisville, Kentucky[4]. The tornado maintained an extended period of damaging conditions throughout its time on the ground with an average speed of 62 mph. It remains the longest continuous track length on record and maintained a width of a quarter to one mile.

There remains some debate regarding whether this damage path was genuinely created by a single long-track tornado or multiple tornados, as conditions made the funnel difficult to distinguish from the clouds it was connected to. Also, there are numerous gaps in the observed damage path greater than a mile long (Figure 1). However, given the amount of time that has passed since the event, and the fact that it was on occasion in a multivortex form, recent research has been unable to determine whether there was just one continuous primary tornado versus multiple separate tornadoes spawned by the long-lived supercell[6].

2.2 Quad-State Tornado

The Quad-State Tornado occurred on 10-11 December 2021 and was actually a family of five distinct tornadoes that left a nearly straight line of destruction over 257 miles across parts of Arkansas, Missouri, Tennessee, and Kentucky. It left 67 dead and at least 516 people injured over a four and a half hour time span. This family of tornadoes was composed of two EF4 wedges separated by a 13-mile span filled with three small tornadoes, one of which was an EF1 and the remaining two reached only EF0 level intensity. Figure 8 depicts the line of damage these tornadoes created across the four states they passed through.

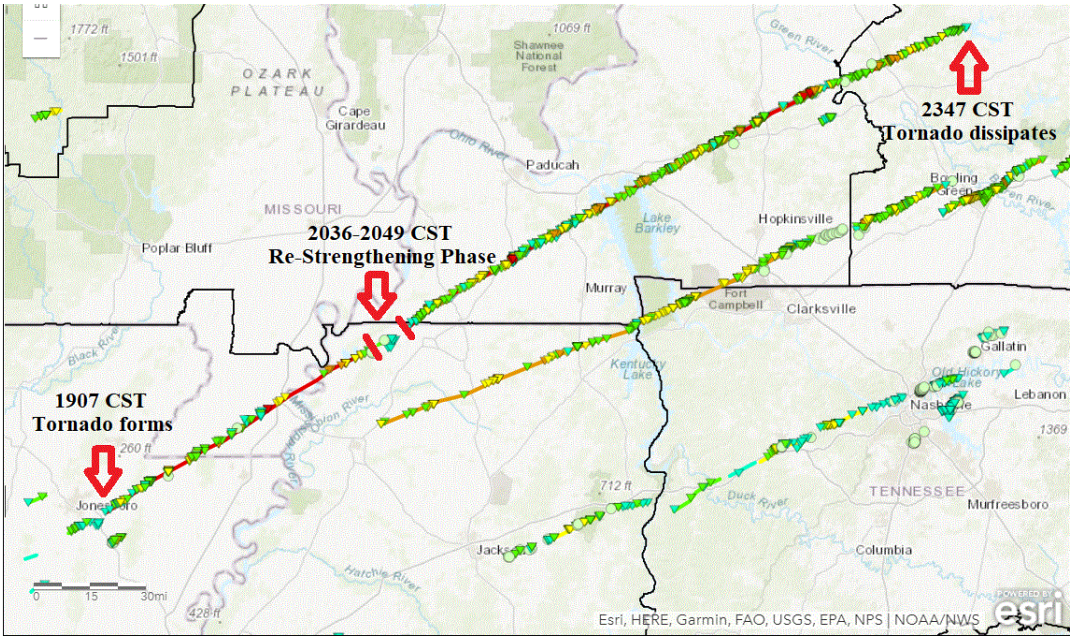

Figure 8. Map depicting damage points and path of the Quad State Tornadoes and additional tornadoes on 10-11 December 2021.[11]

2.2.1 synoptic environment

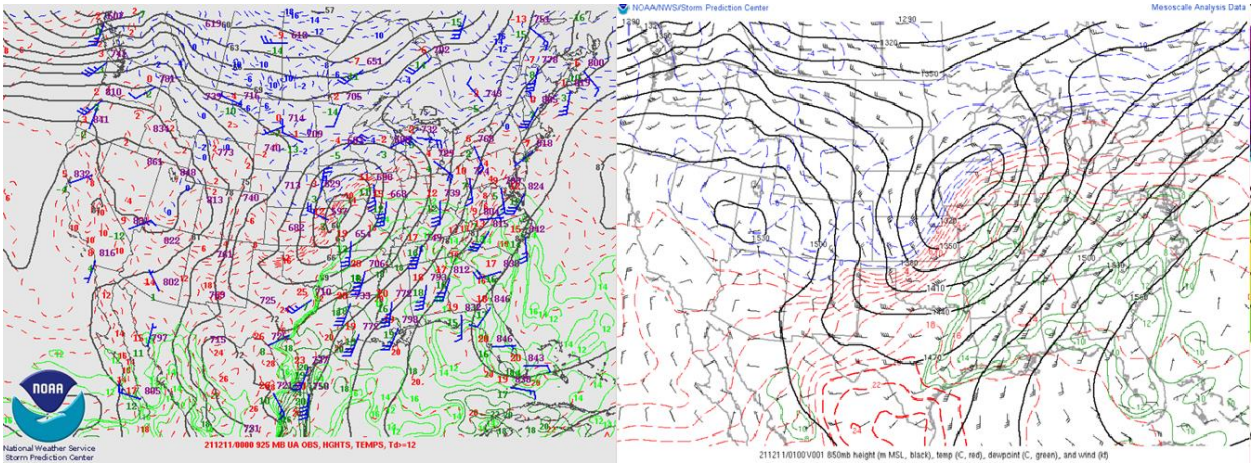

Figure 9. Analysis of heights, winds, and temperatures valid at surface levels (left) and 850hPa (right) at 1800 CST on 10 December 2021.[16]

There were far fewer limitations in observations for the storm system that crossed through the Midwest on 10 December 2021, given the progress that has been made in the meteorological community over the past hundred years. Many more resources are available to the public currently. The area affected by the strongest tornadoes experienced an unseasonably warm and humid winter and a warm and dry spring[3]. The development of an intensifying mid-level trough (Figure 9, right) was observed from 8 December 2021 into 11 December 2021, progressing across the High Plains. By the morning of 10 December, the SPC had issued a moderate risk area for northeastern Arkansas into southern Illinois for severe/damaging thunderstorms and, by 1500 CST, a tornado watch had been issued through portions of Arkansas, Tennessee, Mississippi, Missouri, Illinois, and Indiana. As this trough continued to deepen, a series of mid-level to high-level shortwave troughs came into phase over the area and, alongside the increasing

cyclonic flow aloft, the severe upper wind shear, and the moisture introduced to the system across the Mississippi Valley, it became apparent that a strong and damaging storm would affect the area and lead to dangerous tornadic activity[14]. A triple-point was noted at the center of the low-pressure system associated with this storm as well (Figure 10), though in this case the tornadoes formed approximately four hours after the triple point resolved rather than during its influence, as was seen in 1925[15]. A long-lived supercell formed over Arkansas around 1720 CST 10 December 2021 and lasted until 0100 CST 11 December 2021, traveling over 350 miles before dissipating just past Louisville, Kentucky. The supercell maintained a continuous mesocyclone throughout its life cycle, verified via Doppler radar analysis during the four and a half hours in which the two primary tornadoes wreaked havoc through the central U.S. It appears also that the storm underwent a mesocyclone re-strengthening phase in the time period between the two strongest tornadoes between 2036 CST and 2049 CST. During this time, three smaller tornadoes were observed, but did little damage comparatively[14].

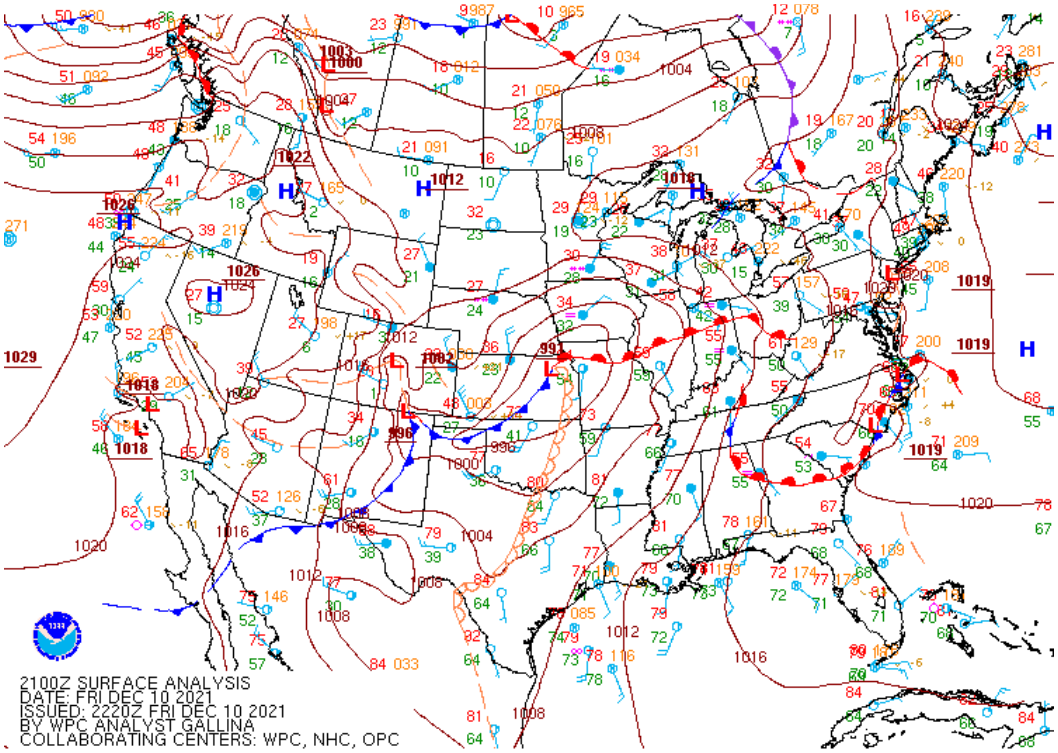

Figure 10. Surface analysis valid at 1500 CST 10 December 2021.[16]

2.2.2 mesoscale environment

A discussion of the Quad-State Tornadoes encompasses an evaluation of a family of five separate tornadoes that all moved across Tornado Alley consecutively, giving the initial impression that a single long-track tornado had formed. Radar reflectivity in Figure 11 allows the viewer to follow the development and movement of the supercell that spawned these tornadoes, as well as the warnings that were put into place as it traveled. The first tornado formed at 1907 CST just north of Bay, Arkansas: a large wedge tornado that reached low-end EF4 levels of damage. This tornado traveled a distance of 81.24 miles with maximum wind speeds reaching 170 mph and traveled through parts of Missouri, Tennessee, and Kentucky. At its widest point, it was nearly a mile wide, and it lasted for 89 minutes. This first tornado took eight lives during its time on the ground, injuring sixteen more. The tornado initially left a trail of EF1 to EF2 damage, quickly intensifying to EF3 damaging winds by the time it reached Monette, Arkansas at 1924 CST. It reached EF4 level damaging winds just east of Braggadocio, Missouri, eventually weakening to an EF2 rating before dissipating at 2036 CST just two and a half miles northeast of Samburg, Tennessee. There is the possibility that the terrain in this area played a role in the weakening of this tornado. As it crossed the Mississippi River, aerial

imagery shows that the tornado widened before dissipating and crossed a steep bluff before reforming as the second EF4 tornado.

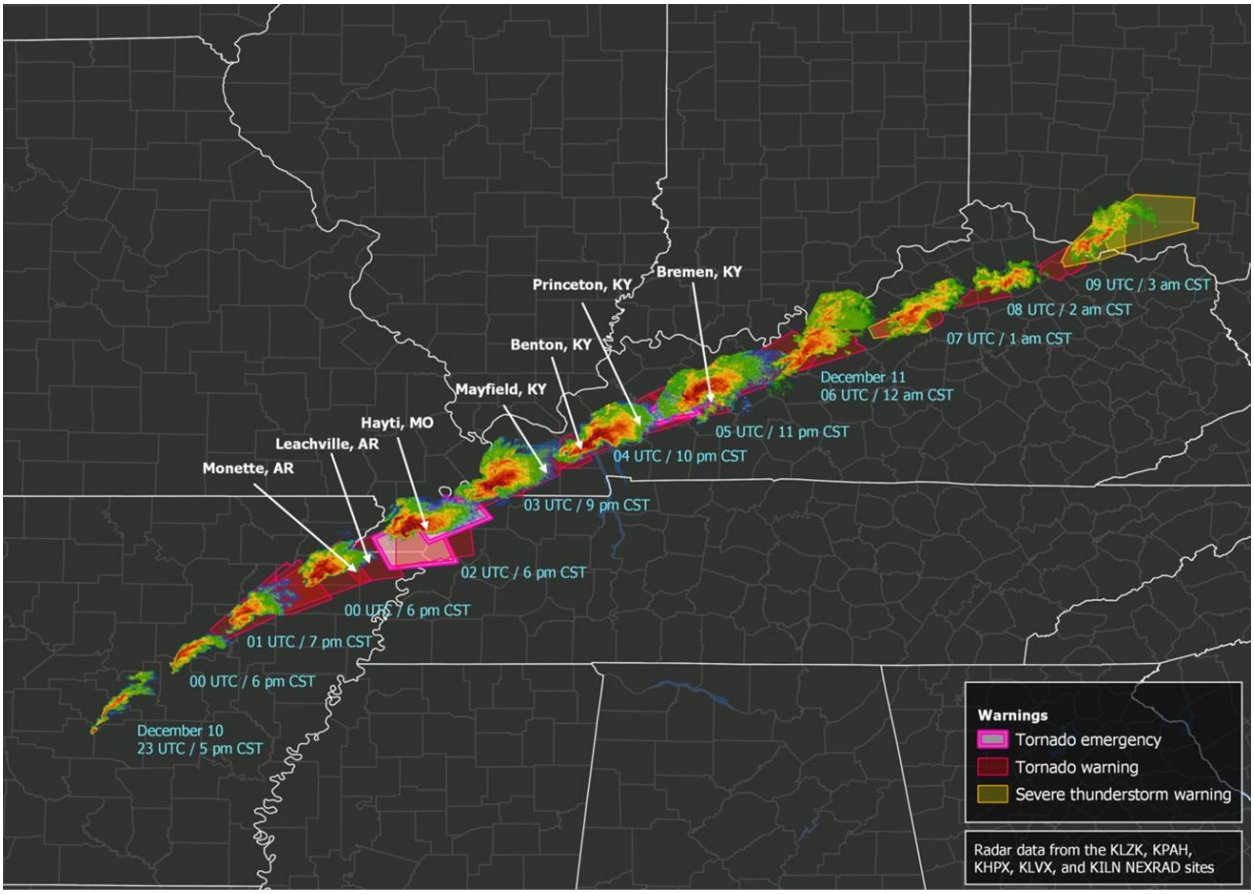

Figure 11. Radar reflectivity following the supercell that spawned the Quad-State Tornadoes on 10 December 2021.

After this initial tornado finished its run, the parent supercell appeared to have entered a cycling phase in which three smaller-scale tornadoes formed, including one EF1 and two EF0 tornadoes, whose paths are depicted in Figure 12. All occurred in Obion County, just northeast of Samburg, uprooting trees along their paths causing some damage to nearby storage buildings. The first was the EF1 tornado that lasted from 2039–2040 CST, the second was the EF0 tornado that damaged the storage buildings, visible from 2041–2044 CST, and the third was another EF0 that occurred from 2043–2044 CST. Figure 8 displays their paths and the location of the reported damages done by these smaller intensity tornadoes. The time between the two EF4 tornadoes lasted only 13 minutes, and the storm had just passed to the northwest of Union City 14 miles from the dissipation point of the first tornado, when the largest and strongest tornado of the five began near Woodland Mills, Tennessee.

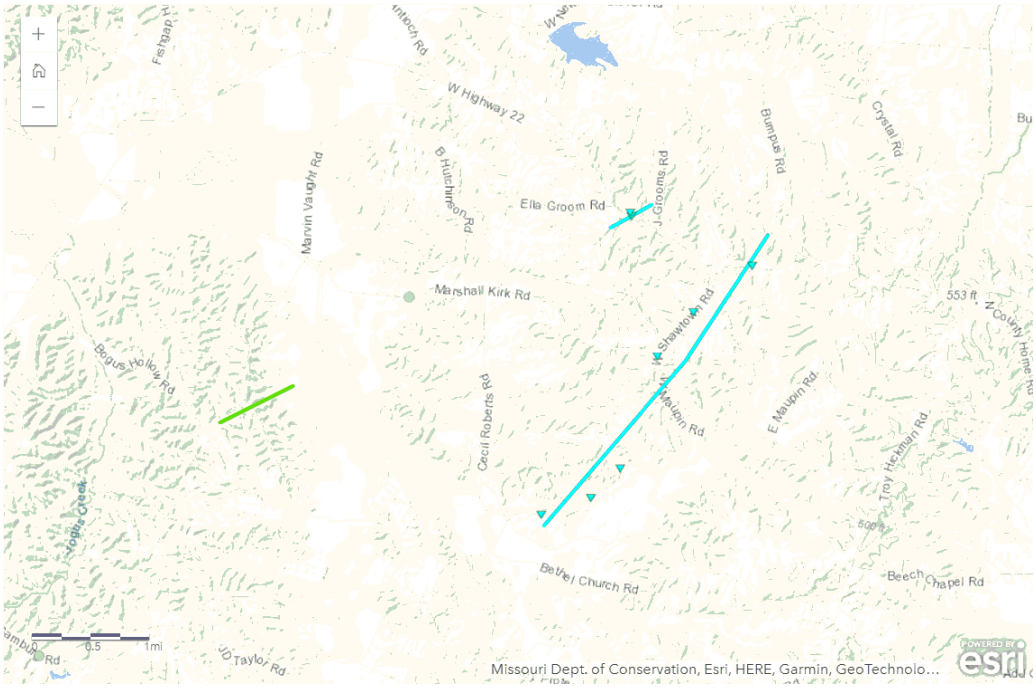

Figure 12. Map depicting damage points and path of EF0 (blue lines) and EF1 (green line) tornadoes that formed between the two primary tornadoes produced by the supercell on 10 December 2021.[11]

The fifth tornado became the deadliest and most damaging produced by this supercell, forming in Tennessee at 2049 CST and entering Kentucky before 2100 CST. This tornado traveled a distance of 166 miles with maximum wind speeds reaching 190 mph. At its widest point, it was a mile wide and was causing damage on the ground for an astonishing three hours. This tornado claimed 57 lives and left over 500 people injured by the time it died out. Before the tornado reached Mayfield, Kentucky at 2126 CST, it had already caused EF4 damage in the small community of Cayce, Kentucky, where a number of hog barns had roofs removed and damage to heavy equipment and homes was noted, including the complete destruction of their fire department. During its time in Mayfield, the tornado proved to be even more destructive, decimating numerous homes and industrial buildings, claiming eight lives in a large warehouse that had been twisted apart. It reached EF4 intensity while crashing through Mayfield, Kentucky, causing catastrophic damage as radar imagery indicated it was tossing debris 9,100 meters into the air. Just before it crossed the Land Between the Lakes National Recreation Area, it once again left a trail of EF4 damage through Cambridge Shores at 2157 CST after having reached its peak level of intensity, destroying homes and businesses and leaving nothing standing along the shore of the lake along its path. EF4 damage continued to be seen throughout multiple communities, aerial imagery of incredible tree damage at Land Between the Lakes appears to show signs of the influence of the terrain on this tornado as well. Similar destruction could be noted until it passed through Bremen at 2300 CST, after which it began to weaken over the next forty-five minutes. It dissipated in the Rough River Dam State Resort Park at 2347 CST. Large hail and damaging winds outside of any visible funnels were noted throughout the duration of the storm as the supercell moved across these four states[11, 12, 14].

3. Results

3.1 Differences

While there are a number of differences between these two storm systems, most appear to be small in scale compared with the overall synoptic setup. The Tri-State Tornado of 18 March 1925 occurred within the first month of the storm season for tornadoes, and so some level of similar storm could have been reasonably expected. The supercell that produced the Quad-State Tornado on 10 December 2021 appeared well outside the expected season, however, and while tornadoes can and do occur at any time of the year it was a less-likely scenario. Likewise, it is interesting to

note that while tornadoes can occur at any point in time during the day, the majority form between 1600-2100 local standard time. Both tornadic events occurred outside of this expected time period, but on opposite ends of it, with the Tri-State Tornado in the morning to early afternoon and the Quad-State Tornado overnight, which put the population at even greater risk as many may sleep through tornado warnings during the night[4]. One must also consider path length. Immediately following the events of 10–11 December 2021, many speculated that the apparent path of the Quad-State Tornado at 257 miles would likely remove the Tri-State Tornado from the running for longest path length. However, as has since been determined, the destructive path taken in 2021 was split into two sections. While both can yet be considered long-track tornadoes, an 81-mile and 166-mile track do not quite compare to the Tri-State Tornado's uninterrupted 219-mile trail of devastation. Another significant difference to note is that it is expected that the Tri-State Tornado developed incredibly close to the associated low-pressure system and was strengthened by the hours its parent supercell remained nestled in the strong baroclinic zone formed by the warm front moving northward in that area. The Quad-State Tornado family, however, formed too far east of its associated low-pressure system to benefit from the effects of the fronts in the same way.

3.2 Similarities

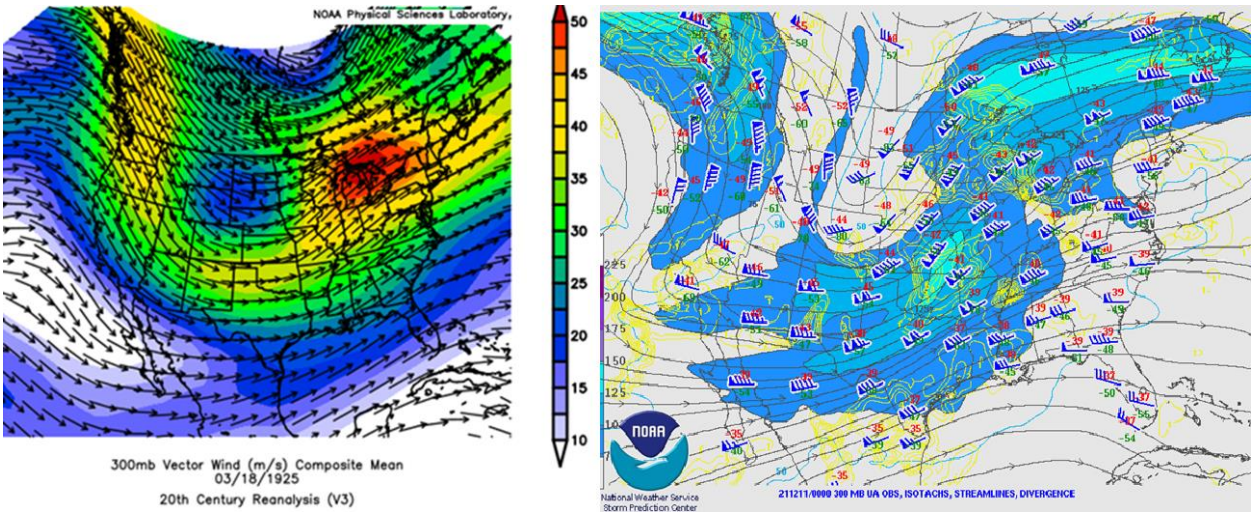

Figure 13. 300hPa maps depicting upper-level winds and associated jet streams on both 18 March 1925 (left) and 10 December 2021 (right).[16]

There are several strong similarities between the Tri-State and Quad-State Tornadoes as well. The tracks of these tornadoes ran very similarly to each other, nearly straight lines moving toward the northeast across the Ohio River Valley. In fact, the two paths are only about 90 miles apart in some areas, making the comparison between them even more understandable as neighboring communities were affected by these storms. Each stemmed from a supercell that spawned multiple other tornadoes, seven reported in 1925 that occurred during the time in which the primary tornado made its way through the Ohio Valley, and five that made up the entirety of the destruction along the Quad-State Tornado's path. Both events spawned from low pressure systems that exhibited triple points in which the fronts intersected with a dryline, and while the Quad-State Tornado occurred too far east for this phenomenon to provide any measurable effect, the presence of the triple point itself may be an important consideration when comparing these natural catastrophes. These severe storms also developed from synoptic scenarios described as "synoptically evident"[13]. Deep upper-level troughs associated with powerful Jet Streams led to favorable conditions, winds at 115+ mph were noted at 500 hPa levels during the Quad-State storm system development and model output of the Tri-State storm system suggest that there was likely a jet associated with that storm as well (Figure 13). Each displayed evidence of warm moist convection reaching up from the Gulf Coast, feeding into the growing instability of the atmosphere (recall Figure 9, which displayed movement of air northward from the Gulf). Along with the intense vertical shear and upward movement of air displayed in both cases (Figure 14) and the cyclonic flow aloft, there are distinct parallels between the two storms leading up to the development of these long-track tornadoes.

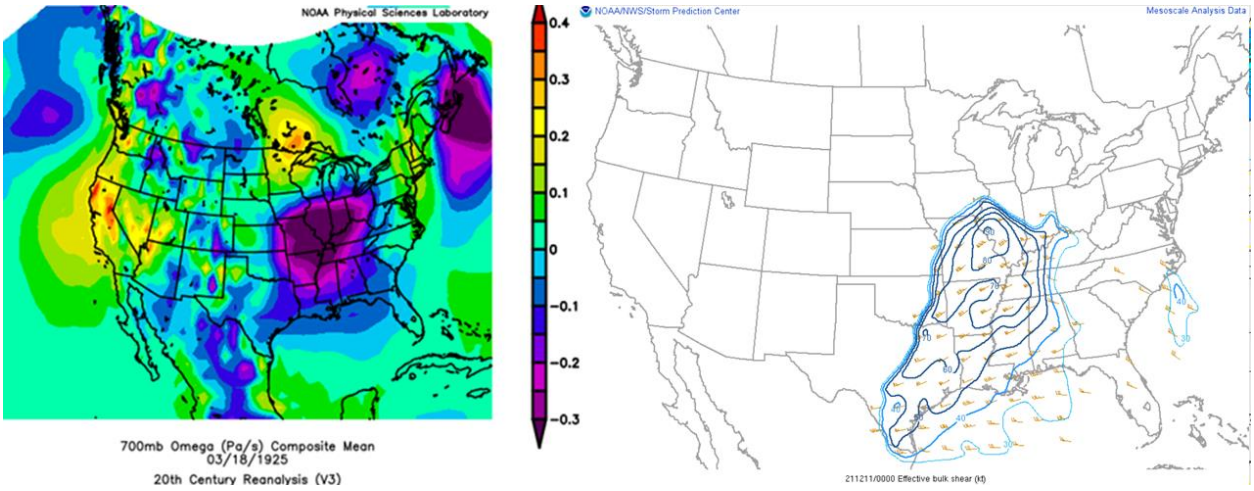

Figure 14. Negative omega indicating upward movement of air on 18 March 1925 (left) and observations of vertical shear on 10 December 2021 (right).[16]

Table 1. Comparison of basic information regarding the Tri-State and Quad-State Tornado events.

	Tri-State Tornado	Quad-State Tornadoes (1st EF4/2nd EF4)
Date & Time (CST)	18 March 1925 1301-1630	10-11 December 2021 1907-2036/2049-2347
Location	Missouri, Illinois, Indiana	Arkansas, Missouri, Tennessee, Kentucky
Duration	3.5 hours	1.5 hours/3 hours
Intensity	EF5	EF4/EF4
Confirmed Tornadoes	1	5
Path Length	219 miles	81.2/165.7
Confirmed Deaths	695	65
Confirmed Injuries	2027	16/500+
Damages (adjusted for inflation to December 2021)9, 15	$3,600,000,000	$3,900,000,000

4. Conclusion

While there are a few distinct differences between these two storm systems, they were remarkably similar. The synoptic events that spawned these storms are not new or even entirely uncommon occurrences. After all, the U.S. experiences such patterns so frequently that they are expected to occur across the country from March through June every year. The fact that the Quad-State Tornado family did almost appear to be shadowing the path of their predecessor in an area close to the first is certainly attention grabbing and may make one wonder if there is something

about this area that encourages such long-track tornadoes to form. Aside from the similar synoptic patterns, many of the same mesoscale elements were experienced in both systems and there is no doubt that both were incredibly powerful, damaging storms.

Given that these long-track tornadoes were spawned from otherwise unremarkable storms there is certainly potential for ongoing research into just what triggers long-track tornadoes to occur. They are not common events by any measure, and we have yet to pin-point any mechanism large or small that would initiate an event so intense or long-lasting. Continued research into this area could be of great benefit to the continued development of severe storm forecasting and warning systems.

5. Acknowledgments

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