

Climatology of Colorado Tornadoes

Are Colorado Tornadoes growing longer and stronger in time?

CHRISTOPHER K. SPEARS

Graduate Student, Mississippi State University

ABSTRACT

Over the past half century, the number of tornadoes reported in the United States has doubled from roughly 600 per year in the 1950s, to around 1,200 per year in the 2000s (Verbout et al. 2006). The trend in Colorado has been more aggressive with the number of average annual tornadoes quadrupling during the same time period, from 12 to 48 per year on average. This trend can be attributed to a number of factors, including an improvement in record keeping and better tornado detection through Doppler radar. It is also widely accepted throughout the meteorological community that a growing population and more public awareness are contributing factors.

There are numerous studies about U.S. tornado trends, but few that focus specifically on potential trends in Colorado. When posing the question ‘are tornadoes growing longer and stronger with time,’ a long-time resident might be inclined to say yes, simply due to recent back-to-back killer tornadoes in the late 2000s. One of those storms struck in late March 2007. Typically, Coloradoans are more concerned about a blizzard rather than a killer tornado that early in the spring season.

So are we seeing tornadoes grow longer and stronger with time? It is the goal of this paper to answer this question and more through a detailed analysis of all documented Colorado tornadoes between 1950 and 2012. Having a better understanding of this weather hazard will help improve public awareness and preparedness that could potentially save lives.

INTRODUCTION. On March 28, 2007, a large and violent EF-3 tornado swept through the small town of Holly, Colorado, just before 8 p.m. local time. Holly is located in the southeast corner of the state in Prowers County, on the western fringe of an area in the United States known as tornado alley. The storm was part of a major outbreak of tornadoes that spanned three days and impacted eight states. The tornado tore a 28-mile path across Prowers County, damaging roughly one-third of the homes in the small town of Holly, and resulted in the first tornado-related deaths in the state since 1960. Less than an hour later, a second long-track tornado touched down in Kiowa County. This storm tracked 11.6 miles into Kansas, but luckily, remained over open country, and did not cause any damage.

thunderstorms that produce tornadoes are most common in the mid-afternoon and early evening hours. In addition to the odd time, this thunderstorm moved very quickly toward the north-northwest, and was surprisingly strong and long-lived for being in such close proximity to the Front Range, where weaker tornadoes are more common (Schumacher et al., 2010). The storm tracked over 30 miles northwest into the mountains of southeast Wyoming, causing significant damage along the way. It was labeled a geographically rare event that could only occur in a limited number of places (Finch and Bikos, 2010).

CLIMATOLOGY. A 1953 research paper about tornadoes in New Mexico, Colorado and Wyoming showed that Colorado tornadoes were an infrequent occurrence, primarily experienced during the late spring and early summer months, with a peak date between June 10-15 and the peak time between 12-7 p.m., along or east of the 105th meridian (Cook, 1953). For the most part, that assessment is still valid today. An analysis of all Colorado tornadoes documented between 1950-2012 (Fig. 2) shows that June is by far the peak month for tornado activity with May and July tied for second place. Since 1950, there have been tornadoes documented in every month of the year except November, December and January. (While not reflected in the modern record, there was a rare killer tornado prior to 1950 that occurred during the month of November. More information on that event can be found later in this section.)

The most opportune time to experience a Colorado tornado is between 11am-11pm with the main peak being between 2pm-7pm local time (Fig. 3). While extremely rare, overnight tornadoes (between 12am-6am) have occurred 26 times since 1950. There has never been a tornado documented in the

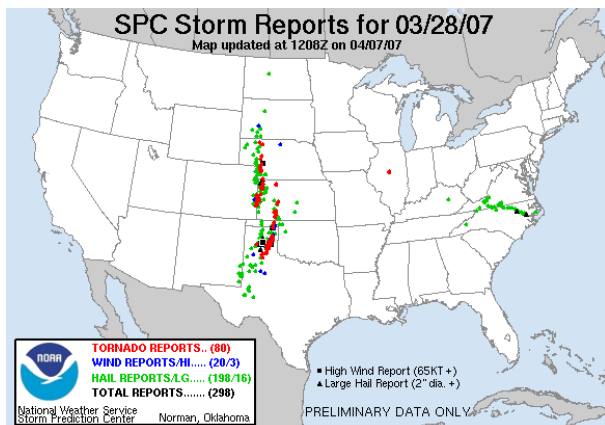


Figure 1: Severe weather reports around the United States on March 28, 2007.

In the following year, on May 22, 2008, another killer EF-3 tornado struck Colorado, but this time, it was much further north and west in the town of Windsor, located along the Interstate 25 urban corridor between Denver and Fort Collins. While this tornado touched down at a time of the year when residents expect severe weather, there were several aspects of the storm that caught most off guard. The storm formed during the late morning hours, contrary to what one typically might expect in Colorado, where

modern record during the 4am, 5am or 8am hours.

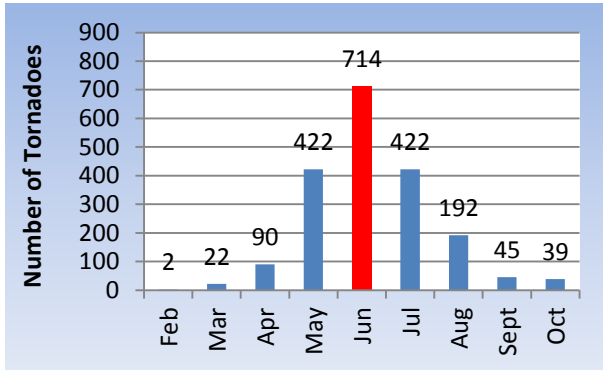


Figure 2: Colorado tornadoes by month (1950-2012).

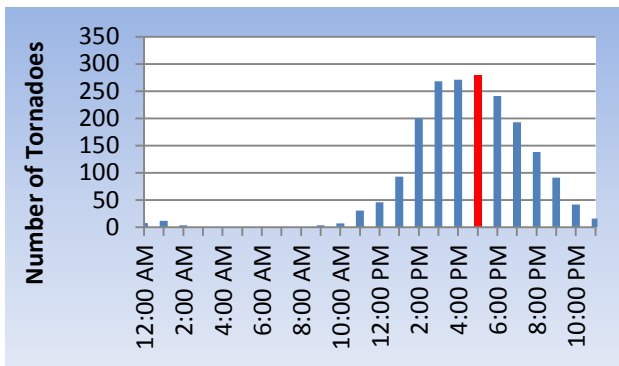


Figure 3: Colorado tornadoes by hour (1950-2012).

To determine the peak date for tornado activity in Colorado, a smoothing technique was applied to the modern tornado record. It was designed to highlight the period of maximum probability for a tornado. This calculation was modeled after the distribution created by Cook in 1953, where the number of tornadoes were tabulated for 5-day intervals between April 1 and September 30. The frequencies were then smoothed by successively overlapping three consecutive 5-day intervals (with frequencies a, b and c) and using the formula $\frac{a+2b+c}{4}$ to smooth the data. The

frequencies were then plotted at the midpoint of each 5-day interval (Fig 4).

The results show that Colorado’s tornado season typically begins in April and builds to a first peak by the end of the month. After a slight decline in early May, the probability of a tornado rapidly increases to a peak that occurs somewhere between May 29th and June 7th. The graph is almost identical to the one that was produced by Cook in 1953 (Figure 5). The only difference is Cook’s peak for Colorado tornadoes was closer to June 10th, and there was not as much detail in the graph since it was built off a much lower number of annual tornadoes.

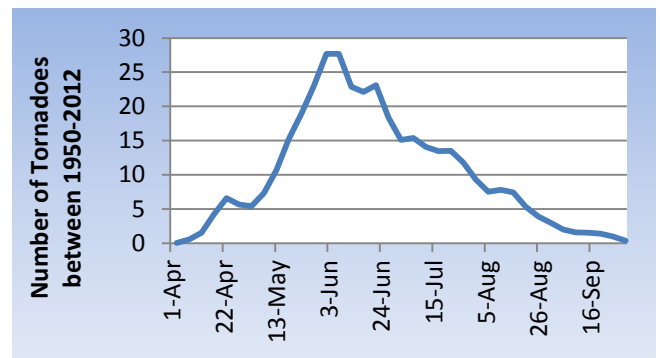


Figure 4: Smoothed frequency distribution of Colorado tornadoes for 5-day intervals, April through September, 1950-2012.

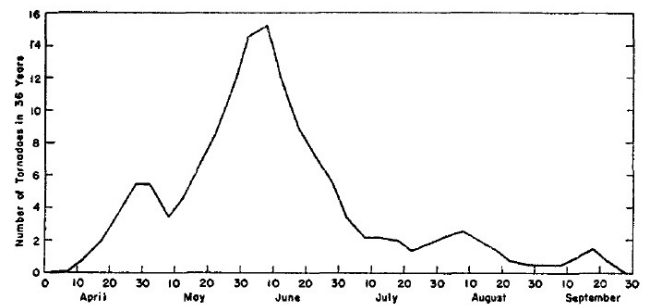


Figure 5: Cooke’s smoothed frequency distribution of tornadoes in Colorado, Wyoming and New Mexico for 5-day intervals, April through September, 1916-1951.

Tornadoes in Colorado are most common on the eastern plains but can occur anywhere at any time, even in the mountains. Since 1950, all but 11 of Colorado's 64 counties have documented at least one tornado. The counties without a recorded tornado include Broomfield, Dolores, Garfield, Gilpin, Gunnison, Hinsdale, Lake, Ouray, San Juan, San Miguel and Summit Counties. (Note: Broomfield County was formed in 2001 from parts of Boulder, Adams and Weld Counties)

For the most part, the counties without a documented tornado contain some of the highest and most rugged terrain in the central Rockies, but elevation doesn't make a location exempt from a tornado. On July 29, 2012, the second highest elevation tornado ever recorded in the United States touched down 40 miles southwest of Denver near the summit of Mount Evans, in Clear Creek County, at 11,900 feet above mean sea level. The tornado tracked 1.75 miles and did not cause any damage or injuries.



Figure 6: Mt. Evans tornado on July 29, 2012. Photo courtesy of 9News.com.

COLORADO'S VERY OWN TORNADO ALLEY. Colorado's most tornado-prone counties are located along and east of Interstate 25 in an area that is heavily influenced by the Denver Convergence-Vorticity Zone (DCVZ). The DCVZ is an area of convergent winds, typically 50 to 100 km in length, oriented in a north to south fashion just east of the Denver metro

area. The zone can often be found extending from Weld County or Morgan County, south toward El Paso County. The DCVZ develops as southeast low-level wind flow interacts with an east-west ridge known as the Palmer Divide (located between Denver and Colorado Springs), and the north-south axis of the Front Range of the Rocky Mountains (Pietrycha et al., 1998). The top 10 counties for tornadoes in Colorado lie along and just east of the DCVZ and account for 59% of the state's total tornadoes since 1950.

Top 10 Counties Colorado Tornadoes 1950-2012	
Weld	252
Adams	158
Washington	133
Elbert	101
Kit Carson	94
Lincoln	90
Arapahoe	85
El Paso	85
Yuma	81
Kiowa	78

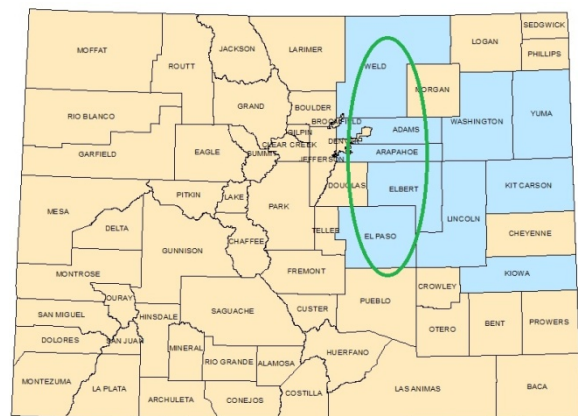


Figure 7: Colorado's top 10 counties for tornadoes with the area most often impacted by the Denver Convergence-Vorticity Zone highlighted in the green circle.

The area along and east of the Interstate 25 urban corridor between Fort Collins and Colorado Springs could conceivably be considered Colorado's very own "tornado alley." The good news is the vast majority of these tornadoes are small, short-lived and often rated F/EF-0, but the bad news is this area has experienced rapid growth since the mid 1990s with the addition of Denver International Airport, the E-470 beltway around the east side of Denver, and a booming oil and gas industry. More people than ever before now live in harm's way during tornado season.

THE DENVER CYCLONE. Another local phenomena that can generate strong to severe thunderstorms is known as the Denver Cyclone, a name given to a mesoscale vortex that forms frequently in eastern Colorado when the large-scale flow is southerly or southeasterly (Crook et al., 1991). It is given the name "Denver Cyclone" because the circulation often sets up over metro Denver as the wind pattern crosses up and over the Palmer Divide and spins anti-cyclonically, pulling cool, dry air off the mountains that collides with the warm, moist air from the south. This feature can sometime co-exist with the DCVZ.

KILLER TORNADOES. Five deaths were attributed to tornadoes in Colorado between 1950-2012.

- June 27, 1960 (Phillips County) - a large F-3 tornado threw two cars a quarter mile, 10 miles north of Holyoke. **2 dead, 4 injured**
- March 28, 2007 (Prowers County) – a powerful EF-3 tornado killed two when it roared through the small town of Holly around 8 pm. **2 dead, 11 injured**
- May 22, 2008 (Weld County, Larimer County) – a massive EF-3 tornado traveled across two counties leaving a path of destruction when it touched down around 11:30 am. **1 dead, 78 injured**
- June 30, 1915 (Bent County) – three homes were destroyed twenty miles southwest of Lamar. **1 dead, 5 injured**
- August 10, 1917 (Baca County) – a man was killed in Two Buttes as he sought shelter inside a dry goods store hit by a tornado that struck around 6 pm. **1 dead, 7 injured**
- November 4, 1922 (Lincoln County) – a rare late season and early morning tornado struck 20 miles north of Sugar City around 5 am. **4 dead, 25 injured**
- November 4, 1922 (Phillips County) – a teacher was killed in her "teacherage" home at the Pleasant Valley School, located 11 miles east-southeast of Holyoke, as a tornado hit around 9:30 am. **1 dead, 3 injured**

Killer tornadoes were much more common in Colorado prior to 1950. One possible cause is that Colorado had a much larger and more active population on the eastern plains during the early 20th century. This population combined with a lack of sufficient warning time, forecasting skill and building code enforcement are likely the main causes for such a high number of fatalities. The following is a list of killer tornadoes prior to 1950 as composed by Grazulis.

- August 10, 1924 (Washington County) – nine children and a woman were killed in a farmhouse near Thurman as a tornado hit around 1:45 pm. **10 dead, 8 injured**
- June 14, 1925 (Pueblo County) – a child was killed as a small tornado hit a farm and poultry house around 1 pm. **1 dead, 2 injured**
- August 10, 1926 (Logan County) – a child was killed when a tornado destroyed two homes near Padroni. **1 dead, 2 injured**
- June 8, 1928 (Baca County) – seven farms were destroyed near the Oklahoma border from a tornado that struck around 4:15 pm. **2 dead, 4 injured**
- June 29, 1928 (Larimer County, Weld County) – Two women died when two farmhouses were destroyed just west of Johnstown from a tornado that hit around 11:45 am. **2 dead, 50 injured**
- October 2, 1930 (Pueblo County) – Three people left their car and sought shelter in a farmhouse 14 miles northwest of Fowler when they saw a tornado around 3 pm. The farmhouse and car were destroyed. **3 dead, 4 injured**
- April 30, 1942 (Bent County, Kiowa County) Four different homes were destroyed near McClave and Eads from an overnight tornado that struck around 1:30 am. **4 dead, 12 injured**

Colorado Tornadoes 1950-2012		
Rank	Number	Percent
F/EF-5	0	0.00%
F/EF-4	1	0.05%
F/EF-3	21	1.08%
F/EF-2	111	5.70%
F/EF-1	531	27.26%
F/EF-0	1229	63.09%
Unrated	55	2.82%
Total	1948	100.00%

CLASSIFICATION OF COLORADO TORNADOES.

The vast majority of the 1,948 tornadoes documented in Colorado between 1950-2012 fall into the lower classifications of the Fujita/Enhanced Fujita scale, but strong tornadoes, while rare, can occur. Colorado has never recorded a tornado that ranks as F/EF-5 on the Fujita or Enhanced Fujita scales. There has only been one F/EF-4 tornado recorded since 1950 but it did not touch down in Colorado. The storm formed during the noon hour near Boise City, Oklahoma, on May 18, 1977, and traveled northeast for 29 miles, crossing into Baca County, Colorado, where the tornado tore a path of destruction for another 9.3 miles before dissipating. No deaths or injuries were reported, but damage was estimated to be \$2.5 million.

DATA AND METHODS. To answer the question posed by this paper, are Colorado tornadoes growing longer and stronger with time, an extensive analysis of all events documented between 1950-2012 was performed. Data on Colorado tornadoes was collected from the National Weather Service Storm Prediction Center (SPC) as compiled for the National Climatic Data Center.

To establish a methodology for answering the main question of this paper an analysis of width and distance traveled was performed on the Colorado tornado database 1950-2012. The data was divided into two categories, width and distance traveled, with each category having four sub-categories; F/EF-0, F/EF-1, F/EF-2 and F/EF-3. Since there has only been one F/EF-4 tornado documented in Colorado and no F/EF-5 storms this study excludes those classifications. It is important to note that tornado ratings in the SPC dataset between the 1950s and early 1970s contain ratings that were performed remotely, primarily via archived newspaper accounts and photos, which were prone to emphasis on higher degrees of devastation (Schaefer and Edwards, 1999). Another factor to consider is the change from the Fujita (F) scale to the Enhanced Fujita (EF) scale in 2007. The total impact of the EF scale on the tornado-rating climatology remains ambiguous in light of previous shocks to the dataset and given the limited sampling time since its February 2007 implementation (Edwards et al, 2013). For the purposes of this study, F and EF rated tornadoes were considered to be in the same category. Some manipulation of the data was performed, in particular, with the reported tornado widths. Those details will be explained within each of the tornado classifications analyzed in this study.

RESULTS

F/EF-3

The F/EF-3 category is the smallest in the study in terms of annual and decadal frequency, but poses the most danger to Colorado residents. F/EF-3 tornadoes account for 1% of tornadoes in the state but are responsible for 47% of tornado-related injuries and 100% of tornado-related deaths during the study period.

Based on the 62 years of data, Colorado can expect to see at least one but no more than six F/EF-3 tornadoes per decade (Fig. 8). On average, there is an F/EF-3 tornado somewhere in the state every three years (Fig. 9). It's rare to get two tornadoes of this strength in the same year; that has only happened 3 times since 1950. It is even less common to see two tornadoes of this magnitude on the same day; that has only happened once, on June 6, 1990.

Tornadoes of this magnitude have been recorded in March, May, June, July, August and October (Fig. 10). The earliest F/EF-3 tornado since 1950 happened on March 28, 2007. The latest on record happened on October 17, 1971. May and June have seen the highest number of F/EF-3 tornadoes since 1950 with 7 each; this magnitude of tornado appears to be most common between the dates of May 15-June 15, when 11 of the 21 documented events have occurred.

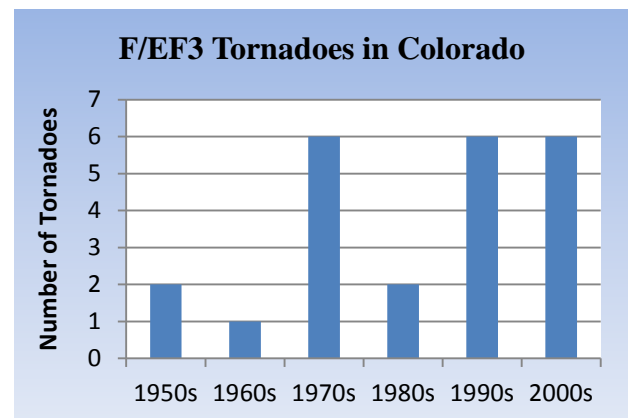


Figure 8: Frequency of F/EF-3 tornadoes in Colorado by decade.

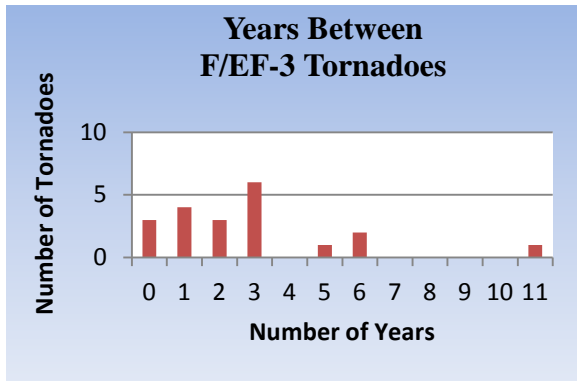


Figure 9: The number of years in between each F/EF-3 tornado event in Colorado (1950-2012).

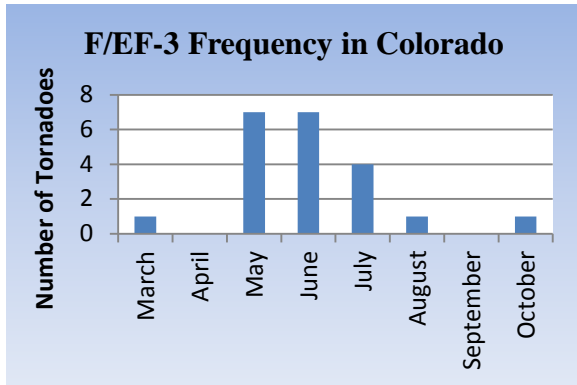


Figure 10: Monthly distribution of F/EF-3 tornado events in Colorado (1950-2012).

The majority of Colorado’s F/EF-3 tornadoes have touched down on the eastern plains, along or east of the heavily populated Interstate 25 urban corridor. More specifically, this class of tornado appears to be most common in the area bounded by Interstate 25 on the west, Interstate 70 to the south, Kansas on the east and Nebraska and Wyoming to the north. It is rare to have a tornado of this strength west of I-25 (Fig. 11). The following counties have experienced an F/EF-3 tornado since 1950: Costilla, Weld (2), Sedgwick, El Paso (2), Adams (2), Washington (3), Logan (2), Kiowa, Denver, Lincoln (2), Elbert, Kit Carson and Prowers (2). Both Kiowa and

Larimer Counties have had an F/EF-3 tornado travel into the county from a neighboring county.

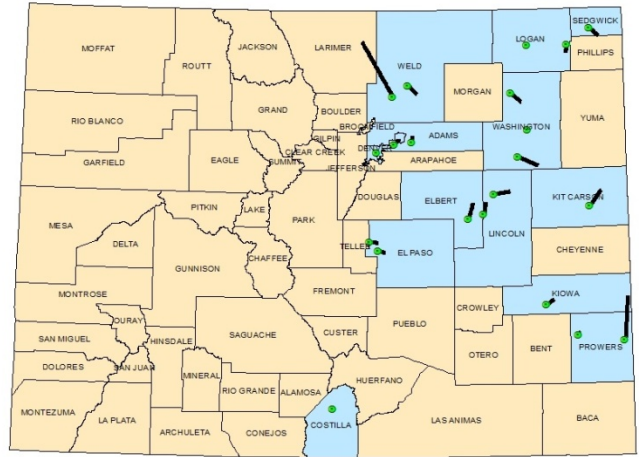


Figure 11: Touchdown locations and paths of F/EF-3 tornadoes in Colorado (1950-2012).

To look for trends in the average width and distance traveled by F/EF-3 tornadoes in Colorado since 1950, a box plot of each was constructed (Fig. 12 and 13). There was no manipulation of the original dataset due to the assumption that tornadoes of this strength were likely thoroughly documented. Stronger events may be more reliably reported than weaker events, but changes in tornado damage assessment procedures still lead to problems in trend identification (Doswell et al., 2009). Despite potential changes in how data was collected, the dataset for F/EF-3 tornadoes in Colorado is small and therefore it must be taken for face value.

The only tornado in the database that looked somewhat suspect was the June 27, 1960 event in Phillips County that claimed two lives. The tornado was reported as having a width of 10 yards, but given the deaths were in cars, it is possible the storm received its rating due to the damage to the

vehicles alone if nothing else was around. The tornado was near the small town of Ovid which is very rural. It is quite possible this tornado was over open land and it just happened some vehicles were on a road in its path.

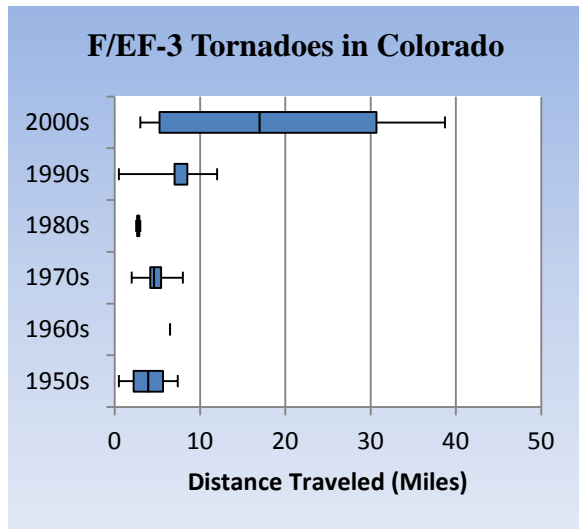


Figure 12: Average distance traveled per decade by F/EF-3 tornadoes in Colorado.

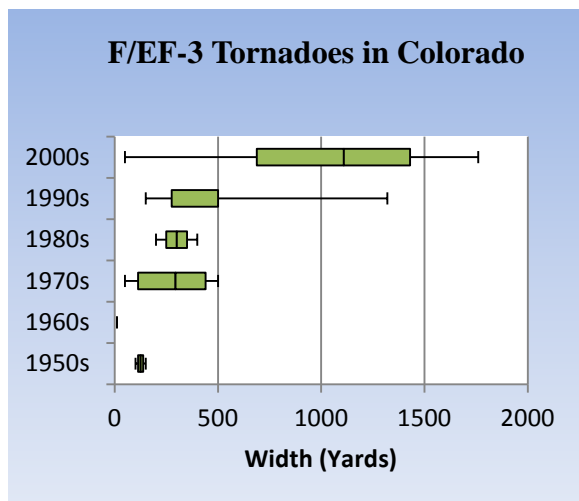


Figure 13: Average width of F/EF-3 tornadoes in Colorado per decade.

There are a few potential trends that can be derived from the box plot of distance traveled by F/EF-3 tornadoes in Colorado. Since 1950, both the average distance and the variability of distance traveled have increased. When looking at the box plot for the width of F/EF-3 tornadoes, both the variability and average width also appear to be increasing. Population was not considered as a factor in this tornado classification because as stated earlier, it is assumed that this strength of tornado has been thoroughly documented. Given that two killer tornadoes struck the state over the past decade, one in a rural and one in an urban setting, at different times of the year and different times of the day, it is easy to think that strong and potentially killer tornadoes are becoming more variable in Colorado, and they are potentially growing longer and stronger when they do occur. Given the rapidly growing population across eastern Colorado, the assumption that F/EF-3 tornadoes are growing longer and stronger with time could be a catalyst to increase public awareness.

F/EF-2

The F/EF-2 tornado accounts for 5.7% of all Colorado events and has caused 38% of all tornado-related injuries since 1950. Based on the 62 years of data, Colorado can expect to see at least 12 but no more than 30 F/EF-2 tornadoes per decade (Fig. 14). On average, there is an F/EF-2 tornado somewhere in the state at least every two years, but it is common to see one almost every year (Fig. 15). 26 out of 62 years have had more than one F/EF-2 tornado reported. The most reported in one year was 8 back in 1976.

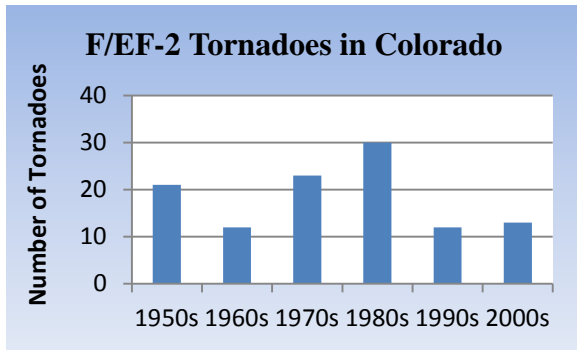


Figure 14: Frequency of F/EF-2 tornadoes in Colorado by decade.

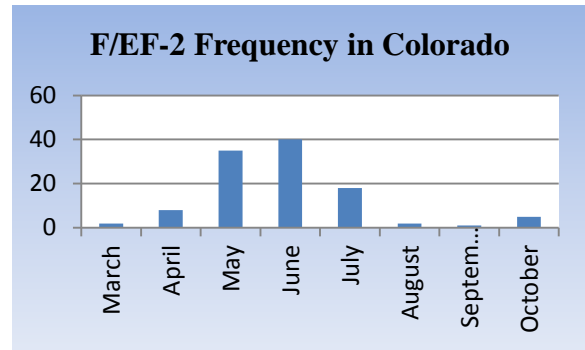


Figure 16: Monthly distribution of F/EF-2 tornado events in Colorado (1950-2012).

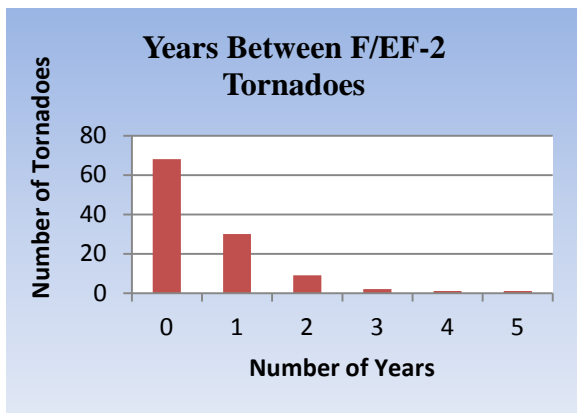


Figure 15: The number of years in between each F/EF-2 tornado event in Colorado (1950-2012).

F/EF-2 tornadoes have been recorded in every month between March-October, with the earliest on March 18, 1977 and the latest on October 20, 1953 (Fig. 16). May and June have seen the highest number of F/EF-2 tornadoes with 56 of 111 events between 1950-2012 occurring between May 15-June 15.

The majority of Colorado’s F/EF-2 tornadoes have touched down on the eastern plains, along or east of the heavily populated Interstate 25 urban corridor. More specifically, this class of tornado appears to be most common in the area bounded by Interstate 25 on the west, Interstate 70 to the south, Kansas on the east and Nebraska and Wyoming to the north. It is rare to have a tornado of this strength west of I-25 (Fig. 11). 33 of 64 counties have documented a tornado of this magnitude. The distribution is as follows...

Adams (8), Alamosa, Arapahoe, Baca (4), Bent (4), Boulder (2), Cheyenne (3), Conejos, Crowley (2), Custer, Denver (2), Douglas (2), Elbert (5), El Paso (6), Huerfano, Jefferson, Kiowa (3), Kit Carson (5), Larimer (3), Las Animas, Lincoln (6), Logan (3), Mineral, Montezuma, Morgan (8), Otero, Park, Phillips (3), Pitkin, Prowers (4), Pueblo, Sedgwick (2), Washington (4), Weld (11) and Yuma (8).

Arapahoe, Kiowa, El Paso, Denver and Weld (3) counties have had F/EF-2 tornadoes travel into their county.

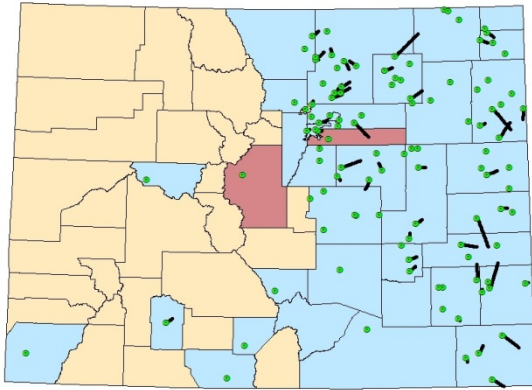


Figure 17: Touchdown locations and paths of F/EF-2 tornadoes in Colorado (1950-2012).

To look for trends in the average width and distance traveled by F/EF-2 tornadoes in Colorado since 1950, a box plot of each was constructed (Fig. 18 and 19). There was no manipulation of the original dataset due to the assumption that tornadoes of this strength were likely well documented. There were 9 tornadoes with a width of 10 yards reported, which does seem suspect, but 4 of the 9 reported injuries so one can only assume there was decent documentation of the event. The other 5 all occurred in the 1950s so it wouldn't make a huge difference in the output.

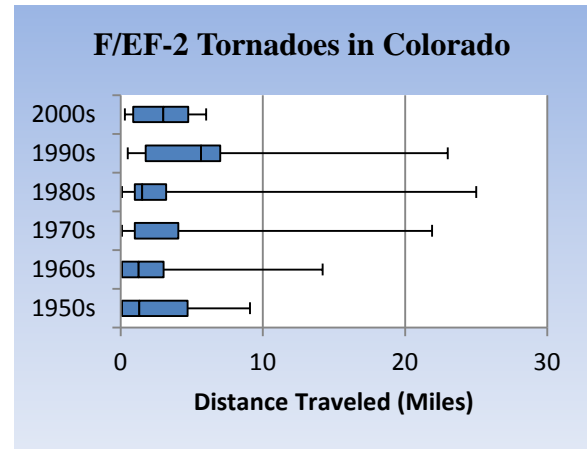


Figure 18: Average distance traveled per decade by F/EF-2 tornadoes in Colorado.

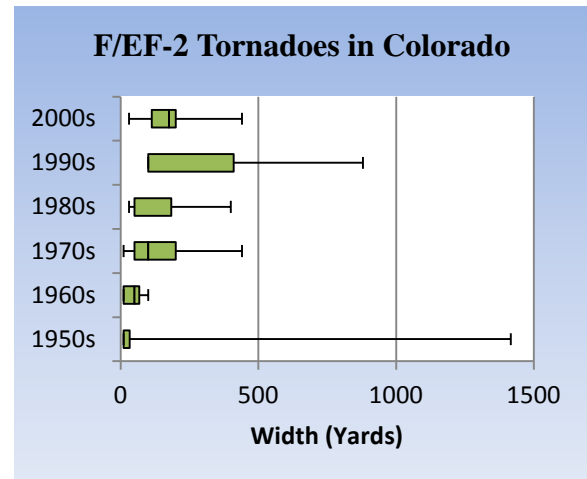


Figure 19: Average width of F/EF-2 tornadoes in Colorado per decade.

Overall, the trend for F/EF-2 tornadoes in Colorado could lean toward a slight increase in strength and length over time, but nothing substantial other than the variability has grown with time on the distance traveled. This could be due to better storm surveys. Population was not considered as a factor in this classification of tornado because as stated earlier, it is assumed that this strength of tornado has been well documented no

matter what type of population setting it occurred within.

F/EF-1

The F/EF-1 tornado accounts for 27% of all Colorado events and has caused 13% of tornado-related injuries since 1950. Based on the 62 years of data, Colorado can expect to see at least 21 but no more than 70 F/EF-1 tornadoes per decade (Fig. 20). The 1980s were an anomaly in the dataset with 275 F-1 tornadoes reported. For the purposes of coming up with the extremes listed above, this decade was removed.

On average, there is an F/EF-1 tornado somewhere in the state at least every two years, but it is common to see at least one per year.

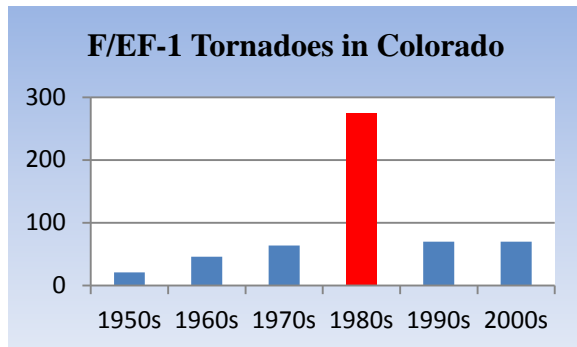


Figure 20: Frequency of F/EF-1 tornadoes in Colorado by decade.

F/EF-1 tornadoes can have been recorded in every month between February and October, with the earliest being February 13, 1954 and the latest October 20, 1963. (Fig. 21). May and June have seen the highest number of F/EF-1 tornadoes with 345 of 531 events.

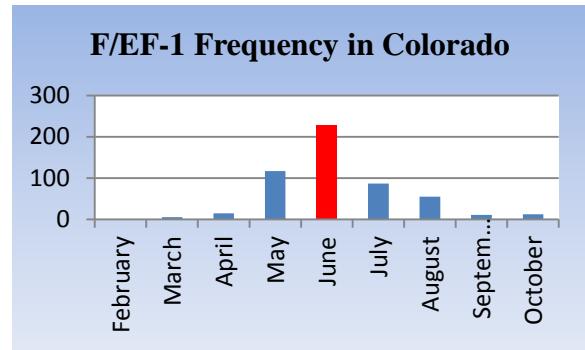


Figure 21: Monthly distribution of F/EF-1 tornado events in Colorado (1950-2012).

The majority of Colorado's F/EF-1 tornadoes have touched down on the eastern plains, along or east of the heavily populated Interstate 25 urban corridor. More specifically, this class of tornado appears to be most common in the area bounded by Interstate 25 on the west, Interstate 70 to the south, Kansas on the east and Nebraska and Wyoming to the north. It is rare to have a tornado of this strength west of I-25 (Fig. 22). 45 of 64 counties have documented a tornado of this magnitude.

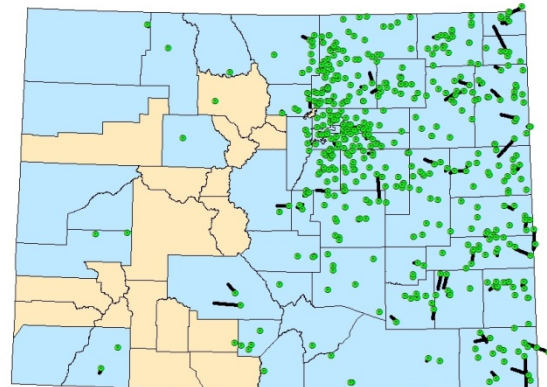


Figure 22: Touchdown locations and paths of F/EF-1 tornadoes in Colorado (1950-2012).

It is rare for an F/EF-1 tornado to travel between counties in Colorado. Since 1950,

only three tornadoes of this strength have crossed a county line. Cheyenne, Morgan and Yuma counties have each had an F/EF-1 tornado enter their jurisdiction.

To look for trends in the average width and distance traveled by F/EF-1 tornadoes in Colorado since 1950, a box plot of each was constructed (Fig. 23 and 24).

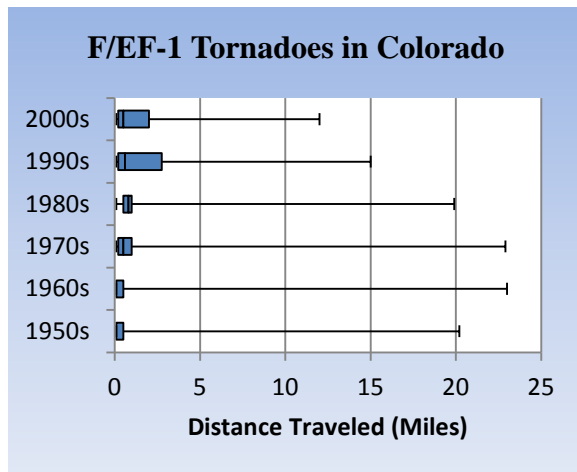


Figure 23: Average distance traveled per decade by F/EF-1 tornadoes in Colorado.

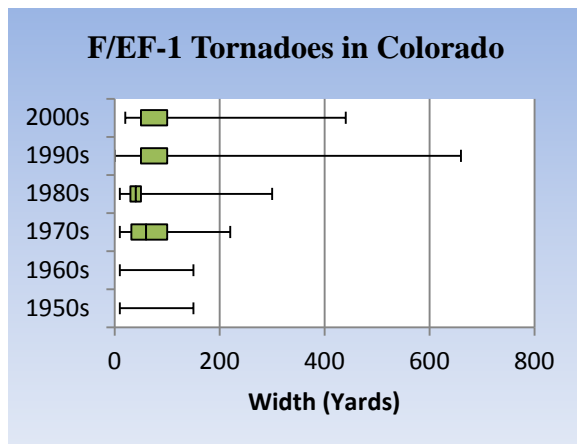


Figure 24: Average width of F/EF-1 tornadoes in Colorado per decade.

Overall, the trend for F/EF-1 tornadoes in Colorado could lean toward a slight increase in strength (width), but nothing substantial is noted over the study period. Population is considered a major factor in the decadal increase of this tornado classification.

F/EF-0

The F/EF-0 tornado is the most common tornado in Colorado and accounts for 63% of all Colorado events and has caused 1% of tornado-related injuries since 1950. Based on the 62 years of data, Colorado can expect to see a few hundred F/EF-0 tornadoes per decade. (Fig. 25). This class of tornado is a yearly occurrence and happens about 48 times per year.

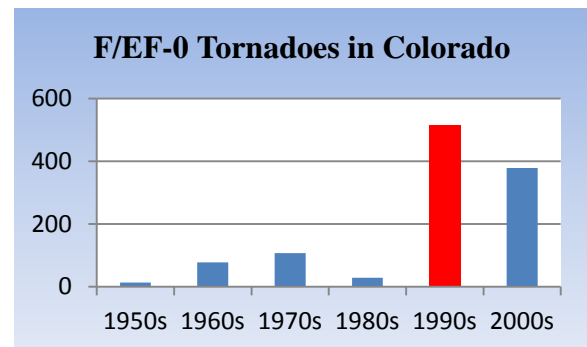


Figure 25: Frequency of F/EF-0 tornadoes in Colorado by decade.

F/EF-0 tornadoes have been recorded in every month between February and October, with the earliest being February 18, 1971 and the latest October 17, 2004. (Fig.26). June and July have seen the highest number of F/EF-1 tornadoes with 722 of 1,229 events.

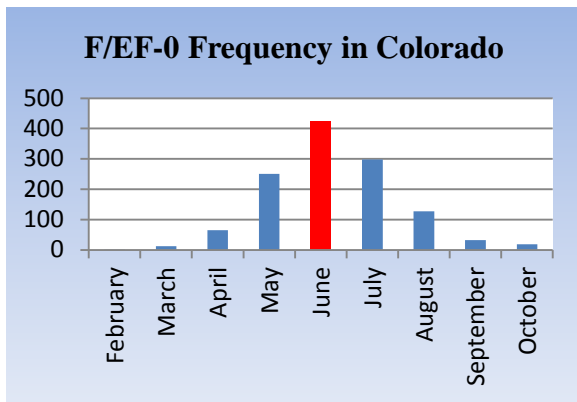


Figure 26: Monthly distribution of F/EF-0 tornado events in Colorado (1950-2012).

The majority of Colorado's F/EF-0 tornadoes have touched down on the eastern plains, along or east of the heavily populated Interstate 25 urban corridor. More specifically, this class of tornado appears to be most common in the area bounded by Interstate 25 on the west, Interstate 70 to the south, Kansas on the east and Nebraska and Wyoming to the north. It is rare to have a tornado of this strength west of I-25 (Fig. 27). 46 of 64 counties have documented a tornado of this magnitude.

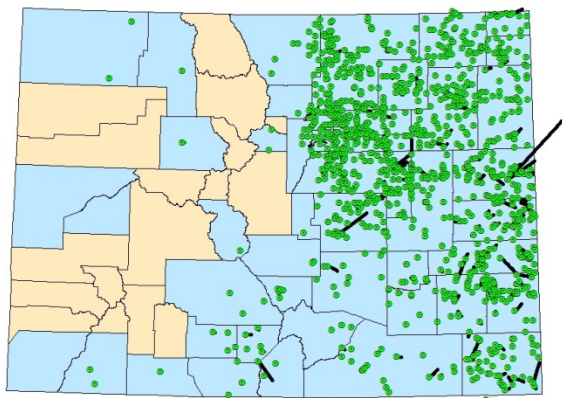


Figure 27: Touchdown locations and paths of F/EF-0 tornadoes in Colorado (1950-2012).

It is rare for an F/EF-0 tornado to travel between counties in Colorado. Since 1950, only five tornadoes of this strength have crossed a county line. Costilla, Lincoln, Otero, Pueblo and Washington counties have each had an F/EF-0 tornado enter their jurisdiction.

When looking at F/EF-0 tornadoes on a decadal timescale, there is a dramatic increase in the number of tornadoes since 1950. Based off the past two decades, Colorado can expect several hundred F/EF-0 tornadoes each decade. The average between 1950 and 1989 was 56 per decade. The average during the 1990s and 2000s was 446 per decade. The 60-year average since 1950 is 186 per decade.

A box plot of the average distance traveled (Fig. 28) for F/EF-0 tornadoes over the past 6 decades shows little difference in the overall distance traveled but there is an increase in the average width (Fig. 29) of this tornado class, revealing a potentially slight increase in overall strength. Population is considered a major factor in the decadal increase of this tornado classification.

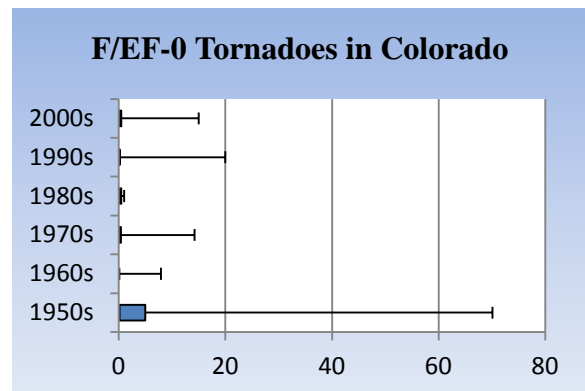


Figure 28: Average distance traveled per decade by F/EF-0 tornadoes in Colorado.

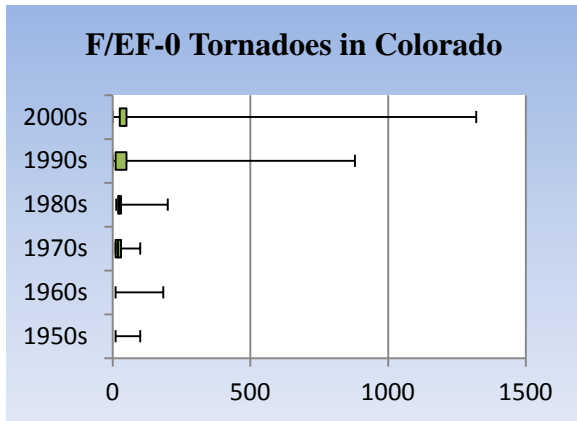


Figure 29: Average width of F/EF-0 tornadoes in Colorado per decade.

CONCLUSIONS

This paper concludes that while tornadoes have definitely increased over the past 60 years, the cause is not exactly clear. One important and likely cause is an increase in public awareness and better forecasting. Another likely cause is the rapidly growing population across Colorado, doubling from 2.5 million to over 5 million in the past three decades. Thousands of people now live, work and play along and east of Interstate 25, where the majority of tornadoes are sighted. Many of these people weren't there 30 years ago, and in many cases around the Denver metro area, as little as 10 years ago. To address the topic of this paper, 'are tornadoes growing longer and stronger with time,' the answer is, it depends on how you look at the question. When it comes to the F/EF-3 tornado in Colorado, it does appear there is a trend toward stronger and more destructive events with a severe threat to life. For the other tornado classifications, F/EF-0, 1 and 2, the trend for stronger tornadoes shows (growing wider) shows up more so than longer (traveling further), but it is dependent upon self-interpretation.

Additional research into relating these trends to specific counties or regions of

Colorado, and making a correlation to population growth may provide a clearer picture as to how much the population and trends of increased tornado behavior may be related. Based off that information, and knowing there is a trend for longer and stronger tornadoes in the state, an assessment could be made to better understand how many are in harm's way, and this information could be used for increased public awareness.

FUTURE RESEARCH

Future research into the climatology of tornadoes in Colorado could include looking at specific weather variables that may help forecasters establish a range of parameters that are associated with the stronger tornadoes in the state, specifically EF-2 and EF-3. Surface moisture, atmospheric temperature and wind direction would be a few variables to be examined. A limiting factor would be how far back in the record hourly data would be available at major reporting stations in the most tornado-prone areas of Colorado (i.e. tornado alley or the top 10 counties).

References

Cook, A.W., 1953: Summary of tornadoes in Colorado, Wyoming , and New Mexico. *Mon. Wea. Rev.*, **Mar. 1953**, 74-76.

Finch, J., and D. Bikos, 2010: A long-lived tornadic supercell over Colorado and Wyoming, 22 May 2008. *Electronic J. Severe Storms Meteor.*, **5** (5), 1-27.

Schumacher, R.S., D.T. Lindsey, A.B. Schumacher, J. Braun, S.D. Miller, and J.L. Demuth, 2010: Multidisciplinary analysis of an unusual tornado: Meteorology, Climatology, and the communication and interpretation of warnings. *Wea. Forecasting*, **25**, 1412-1429.

Verbout, S.M., H.E. Brooks, L.M. Leslie, and D.M. Schultz, 2006: Evolution of the U.S. tornado database: 1954-2003. *Wea. Forecasting*, **21**, 86-93.

NOTE

This section is incomplete.