Minnesota USA Tornado Frequency and Intensity from 1997 to 2012

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Abstract

This study investigates the frequency and intensity of tornados in Minnesota USA from 1997 to 2012. Tornado data from the National Oceanic and Atmospheric Administration (NOAA) website were analyzed using ArcGIS 10.2.2 and Microsoft Excel. Grid geometry was used rather than county or ZIP code to remove bias associated with areas of an irregular size and shape. Findings show the northeast corner of Minnesota has few tornados compared to the rest of the state. The southern half of Minnesota had more intense tornados, and had tornados earlier and later in the season than the northern half of the state.

Introduction

Significance of Minnesota Tornados

This study was aimed at providing a clearer understanding of Minnesota tornado frequency and intensity. Minnesota is often omitted in discussions of tornados and since there is no clear definition for the boundaries of tornado alley, it is unclear whether or not the southern part of Minnesota falls within it (Figure 1).

Data indicates that Minnesota's tornados are of significance. For example, on average Minnesota experiences more tornados in July than any other state (Storm Prediction Center, 2015). In 2010, Minnesota experienced more tornados than any other state across the entire tornado season (Huttner, 2010).

Fujita and Enhanced Fujita Scales

The original Fujita (F) Scale was developed by Dr. Tetsuya Fujita in 1971 (McDonald and Mehta, 2004) in response to the need for a system by which tornados could be compared. The Fujita Scale primarily rates tornados by the amount of damage they cause and then ties the intensity of damage back to wind speed.

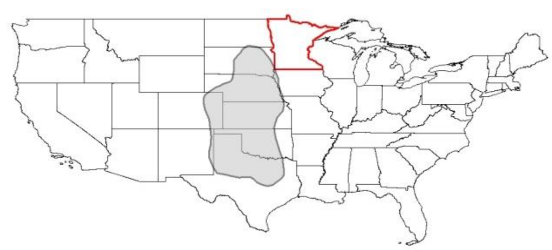

Figure 1. The grey area represents tornado alley as it is approximated by the National Climatic Data Center (NCDC). This depiction of tornado alley was obtained by geo-referencing and onscreen digitizing a raster from the NCDC website. The outline of Minnesota is shown in red. State boundary data was downloaded from the US Census Bureau, Geography Division (2014) website.

The Enhanced Fujita (EF) Scale was created by Dr. James R. McDonald and Dr. Kishor C. Mehta in 2004. There was a need for an updated scale that was

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more consistent and refined than the original Fujita Scale. The EF Scale also uses structural damage to estimate wind speed and utilizes 28 unique "damage indicators" and accounts for structural integrity (Edwards, 2015). Table 1 shows the wind speed comparisons between the F and EF scales. Tornados with a rating of two or higher on either scale are considered to be significant (Edwards).

Table 1. A summarization of the difference in wind speed between F and EF tornado ratings. Wind speed is defined here as the speed of a three-second gust in miles per hour (McDonald and Mehta, 2004).

F or EF Rating	F Wind Speed (mph)	EF Wind Speed (mph)
0	45-78	65-85
1	79-117	86-110
2	118-161	111-135
3	162-209	136-165
4	210-261	166-200
5	262-317	>200

The tornado data used in this study were rated with the Fujita Scale until 2007 when the transition was made to the Enhanced Fujita Scale (Carbin, 2010).

Methods

Data Collection

Data were downloaded from the Storm Prediction Center (SPC) (2015) section of the NOAA website. The data were in CSV format organized by decade for older records and by year for the most recent records. The files contained latitude, longitude, date, time, and F or EF rating for tornado records. The CSV files were imported into Microsoft Excel and saved in the 1997-2003 XLS format for compatibility with ArcGIS. At this stage the files contained records for the entire nation so records outside Minnesota were removed before the files were appended to a Minnesota master file. The master XLS file was used to graph summaries for annual tornado totals, averages, and intensities.

Once appended, the master file was imported into ArcMap 10.2.2 for spatial analysis. The SPC data included latitude and longitude fields for the starting point of each tornado path and these fields were used to display the point data. The geocoded points were saved as a point feature class in the project database.

Grid Analysis

The point data were aggregated into a polygon feature class to quantify the number of tornados for various regions of the state. This could have been achieved by county or ZIP code boundaries but a 20 km by 20 km grid was selected to eliminate the irregularity of the size and shape of features in the aforementioned geometries. The use of a grid for this analysis is similar to that used by Ashley (2007). In Ashley (2007), a grid cell size of 60 km by 60 km was selected to display data across the entire United States. A 20 km by 20 km cell size was selected for this study due to the smaller geographic area.

The grid was created with the Create Polygon Grid Wizard from the Data Reviewer toolbar in ArcMap 10.2.2. The output was a grid with each cell measuring 20 km by 20 km projected in UTM Zone 15N (Figure 2).

Spatial joins were performed between the grid and the point feature classes to allow maximum, minimum, average, and sum values to be examined. The joins were performed for two time periods, from 1950 to 2012 and from 1997 to 2012. These time periods were selected due to the drastic improvements to weather instruments and technology since 1950. There have been continuous improvements made from 1997 to 2012 as well but the development of the NEXRAD Doppler radar network from 1990 to 1996 was a milestone and may have impacted the frequency of tornado reports (Bradford, 2001).

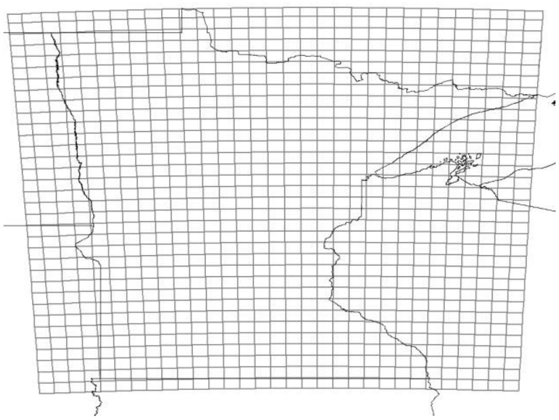

Figure 2. A grid with a 20km by 20km cell size created with the Create Polygon Grid Wizard.

Hot Spot Analysis

To study the density of the raw point data, a ‘hot spot’ analysis was performed on the tornado point feature class. This task was performed in ArcGIS 10.2.2 using the Kernel Density tool from the Spatial Analyst tools. The ‘hot spot’ analysis was first used to examine all Minnesota tornados from 1997 to 2012, but this was later expanded to analyze the density of tornados by F/EF ranking.

Statistical Analysis

Over the course of this study, there appeared to be some patterns emerging in the data. Several statistical analyses were performed to determine if these patterns were significant. For this purpose, the state was divided into 9 regions (Figure 3) and the tornado point data were aggregated into their respective regions. To perform a goodness of fit Chi-Square (x^2) analysis, expected values needed to be calculated. This was completed by using the fraction of the area of Minnesota that fell into each region and multiplying it by 748, the total number of tornados from 1997 to 2012. For example, region 6 only contains 5.5% of the state so the expected number of tornados is 41 (5.5% of the 748 total).

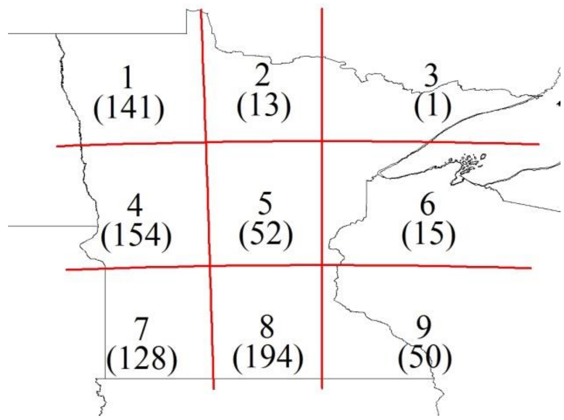

Figure 3. Regions selected for performing t-test and Chi-Square analyses. The number in parentheses represents the number of tornados observed in that region from 1997 to 2012.

The Chi-Square analysis was performed three times. First on all regions, second on only the regions with fewer than the expected number of tornados (2, 3, 5, and 6) and third on the regions with more than the expected number of tornados (1, 4, 7, and 8). Region 9 was not used in either Chi-Square analysis because it was the only region where the observed value was within 5% of the expected value. The variables and formula used were:

O_i = observed tornado count by region
E_i = expected tornado count by region

$$x^2 = \sum \frac{(O_i - E_i)^2}{E_i}$$

A second goodness of fit Chi-Square analysis was performed, this time on the annual tornado counts for the 16 year time period of 1997 to 2012. The same equation shown above was used, but the observed values were the annual tornado counts and the expected values were all 46.75 (1/16 of the 748 total observed tornados).

The third statistical analysis was a parametric Student's t-test which compared tornado counts by region for two time periods, 1974 to 1989 and 1997 to 2012 (Table 2). The 16 year time period of 1974 to 1989 was selected for this analysis because it spans the time period immediately before NEXRAD (implemented in 1990) (Bradford, 2001).

Table 2. Tornado counts by region for the time periods of 1974 to 1989 and 1997 to 2012.

Region	1974-1989	1997-2012
1	40	141
2	13	13
3	7	1
4	46	154
5	37	52
6	6	15
7	45	128
8	88	194
9	32	50

Results

Tornados from 1950 to 2012

The original sample size was to span the entire collection period for Minnesota tornado records, beginning in 1950 and ending in 2012. Early analysis showed a stark increase in tornado frequency over this time period, with records showing only one tornado in 1950 and 36 events in 2012 (Figure 4).

An examination was made of the average F and EF levels for each year by summing all the F and EF values for a given year and dividing by the number of recorded tornado events for that year (Figure 5). Figures 4 and 5 show an increase in frequency but a decrease in intensity over the time period of 1950 to 2012.

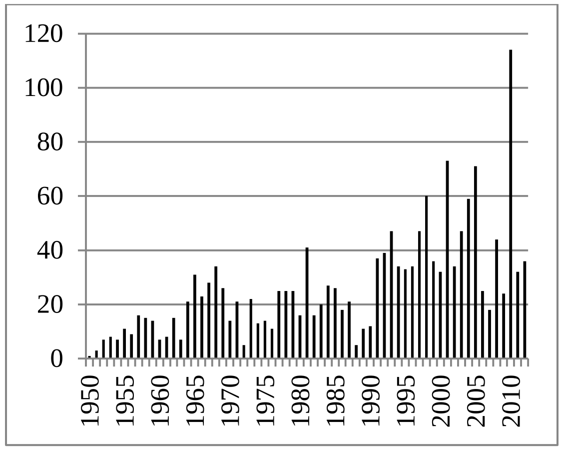

Figure 4. Total number of recorded Minnesota tornados annually from 1950 to 2012.

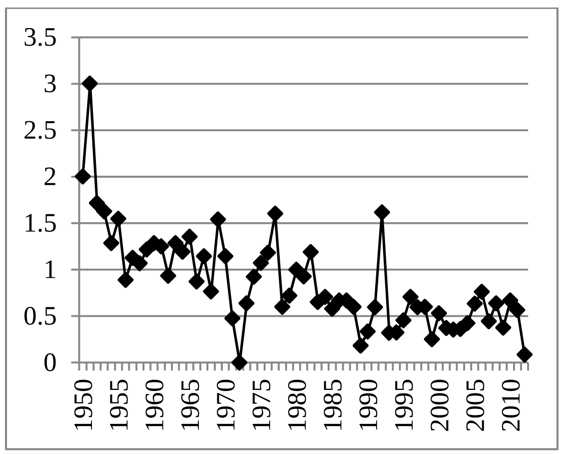

Figure 5. Average F or EF value annually from 1950 to 2012.

Doswell (2007) attributes the apparent increase in tornado frequency to the under reporting of weaker (F0 and F1) tornados early in the tornado record. To test the applicability of this theory on Minnesota's tornados, F0 and F1 tornados were removed from the totals shown in Figure 4, the resulting trendline is nearly flat over the 63 year period with a slope of only 0.0222 (Figure 6) and is not statistically significant ($p > 0.05$). Figure 7 shows only F0 and F1 tornados and this trendline has a slope of 0.6864, an increase of more than one tornado every two years.

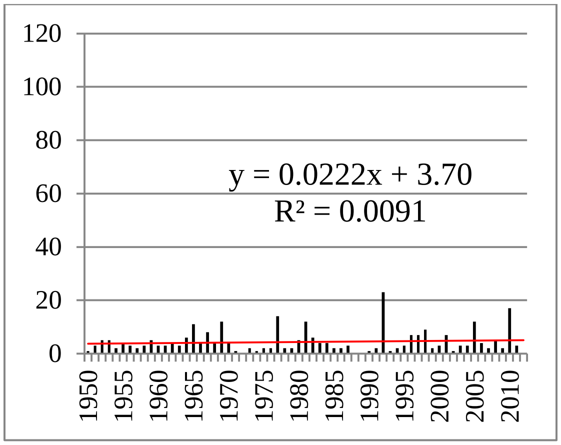

Figure 6. Total tornados rated F2 and higher for each year from 1950 to 2012. A trendline is shown in red.

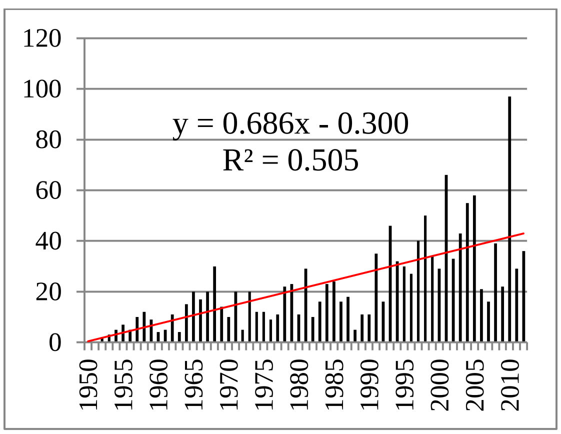

Figure 7. Total tornados rated F0 or F1 from 1950 to 2012. A trendline is shown in red.

Tornados from 1997 to 2012

Tornados that took place from 1997 to 2012 have a much more ambiguous distribution in terms of annual totals (Figure 8). The vast majority of these tornados were rated either zero or one and are therefore considered to be less significant (Edwards, 2015). Figure 8 also shows the percent breakdown of three ranges of tornado intensity (0-1, 2-3, 4-5). Tornados rated zero or one composed at least 80% of the recorded tornados each year and they peaked at 100% in 2012.

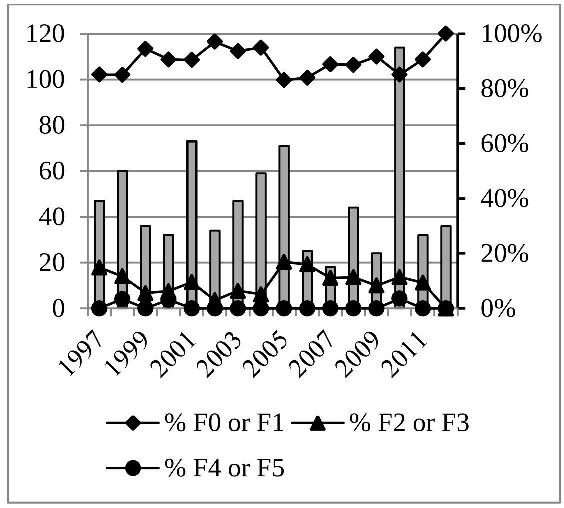

Figure 8. Bars show the number of tornados annually from 1997 to 2012. The % of tornados from each F or EF range in a given year is shown by the marker lines.

The Chi-Square analysis testing the year-over-year distribution of tornados from 1997 to 2012 found that the data did not occur equally over the years. The calculated x^2 of 185.73 was much greater than the critical x^2 value of 24.996 $P[(x^2=185.73) < 0.001]$.

The Student’s t-test comparing tornado counts from 1974 to 1989 and 1997 to 2012 also found there to be some variability in the data. The absolute value of the calculated one-tailed t value was found to be 2.913, which was greater than the critical t value of 1.860 (p=0.0095). This confirms there was a highly significant increase in tornado observations between 1997 to 2012 and an increase in tornado frequency over the 1974 to 1989 timeframe.

The spatial distribution of tornados from 1997 through 2012 reveals a tornado void in the northeast part of the state (Figure 9). The highest concentrations of tornados were in the south central and northwest regions of the Minnesota. The Chi-Square analysis performed on all of the Minnesota regions (Figure 3) confirms an uneven distribution across the state. The critical x^2 value is 15.507 which is substantially less than the calculated x^2 of 320.34 $P[(x^2=320.34) < 0.001]$. This statistically shows that tornados did not occur equally throughout the state. The Chi-Square analysis performed on regions with fewer than the expected number of tornados (2, 3, 5 and 6) provided a calculated x^2 of 167.42, much greater than the critical x^2 of 7.815. This statistically shows the low frequency of tornados in these regions is highly significant $P[(x^2=167.42) < 0.001]$. The Chi-Square analysis on regions with more than the expected number of tornados (1, 4, 7, and 8) provided a calculated x^2 of 152.84, much greater than the critical x^2 of 7.815. This statistically shows the high frequency of tornados in these regions is highly significant $P[(x^2=152.84) < 0.001]$.

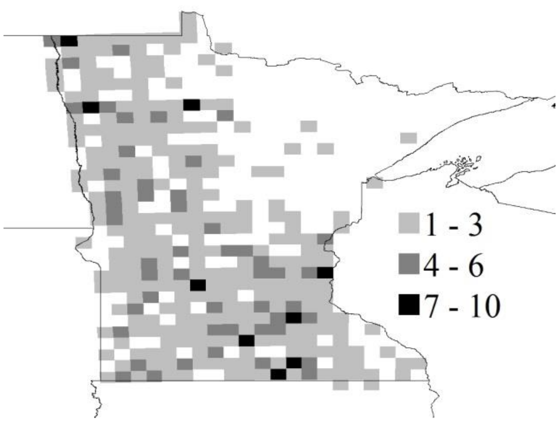

Figure 9. Total number of tornados per grid cell from 1997 to 2012. White space represents areas with no tornados over the time span.

Figure 10 illustrates the distribution of average tornado intensity from 1997 to 2012. The southern half of the state contains all grid cells with an average rating of two or higher. This is reinforced by Figure 11 which shows the highest rated tornado a region experienced over the 16 year time period. The farthest north EF (or F) 4 tornados occurred near Wadena, MN – west of Brainerd.

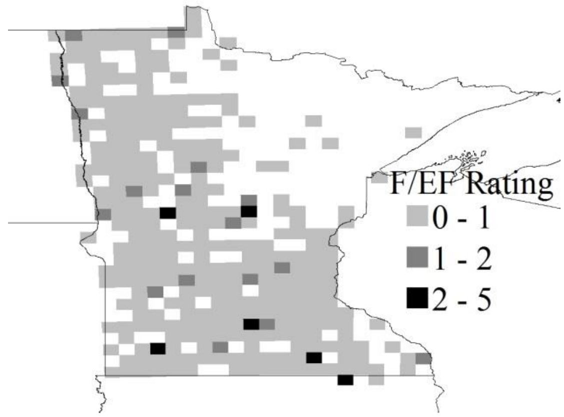

Figure 10. Average F or EF rating for all tornados in each grid cell that occurred from 1997 to 2012. White space represents areas with no tornados over the time span.

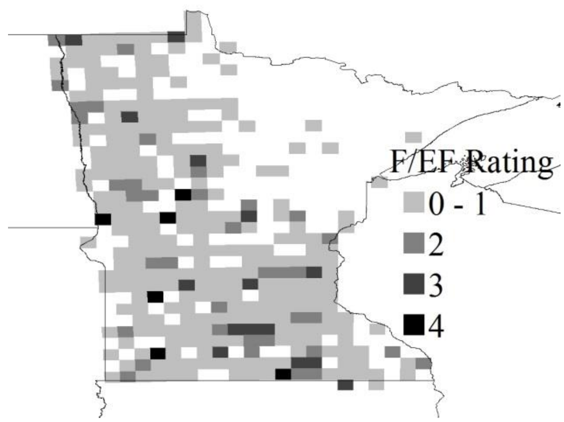

Figure 11. Highest F or EF rating of any tornado occurring from 1997 to 2012. White space represents areas with no tornados over the time span.

Hot Spot Analysis

The 'hot spot' map that was generated based on the kernel density of all tornados from 1997 to 2012 shows peak areas similar to the findings of the 20 km by 20 km grid methodology. The two highest density levels create a band ranging from Albert Lea in southeast Minnesota to Crookston in the northwest (Figure 12). The F0 density map shows a very similar distribution (Figure 13). The F1 density map is unique from all the other ‘hot spot’ maps generated for this study (Figure 14). It shows one area, east of Moorhead, with a dominant density of F1 tornados compared to the rest of the state.

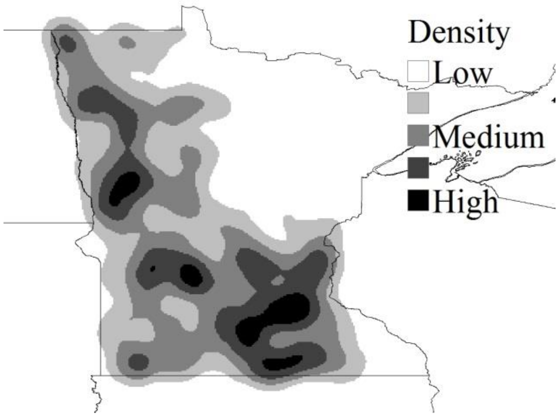

Figure 12. ‘Hot spot’ map of all tornados in Minnesota from 1997 to 2012.

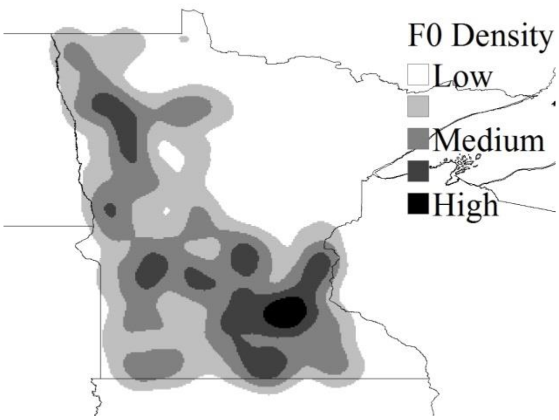

Figure 13. ‘Hot spot’ map of all F0 tornados in Minnesota from 1997 to 2012.

The figures showing the density of F2 and F3 tornados show much more dominant clusters (Figures 15 and 16). The clusters in the F2 and F3 figures show the highest density area covering Albert Lea and Mankato. The F2 map shows additional areas with high density in Otter Tail, Polk and Kittson counties. In the 16 year period examined there were only seven F4 tornados, so a ‘hot spot’ map was not possible due to the small sample size. Figure 17 shows the distribution of F4 tornados across the state. All seven occurred south of the 47th parallel. The two closest together occurred on the edge of Otter Tail county, southwest of Wadena. The others occurred in Wilkin, Chippewa, Murray, and Freeborn counties.

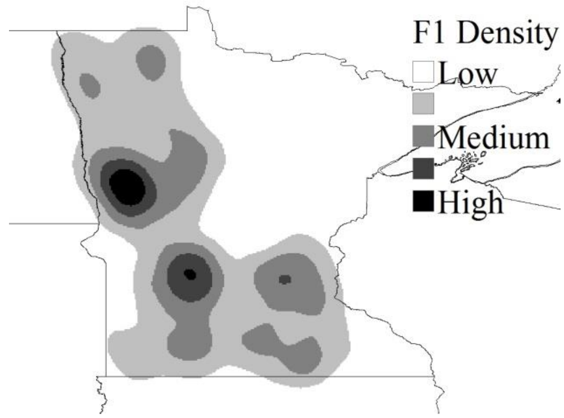

Figure 14. ‘Hot spot’ map of all F1 tornados in Minnesota from 1997 to 2012.

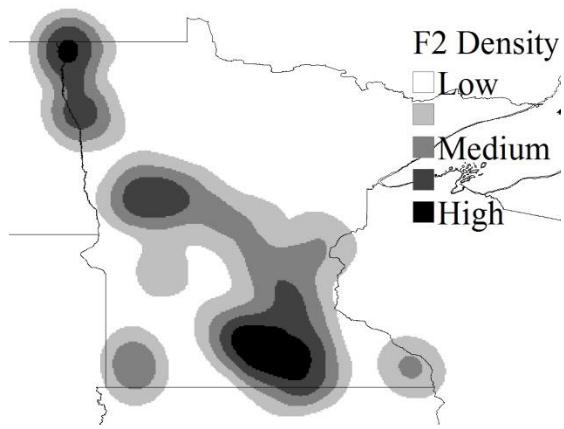

Figure 15. ‘Hot spot’ map of all F2 tornados in Minnesota from 1997 to 2012.

Seasonal Analysis

An examination of the timing and distribution of Minnesota tornados relative to the time of year for the time period of 1997 through 2012 was also undertaken (Figures 18 and 19). June had the highest total number of tornados and July had the second highest.

Spatially, tornados that occurred at the beginning of the tornado season

(March through April) were observed at lower latitudes (Figure 19). Table 3 shows this to also be true for tornados toward the end of the season. This also shows that tornados are recorded at lower latitudes earlier in the year and only three tornados occurred north of the 49th parallel, all three occurring in June and July.

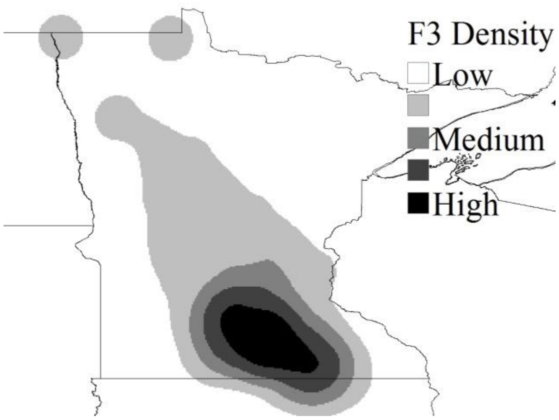

Figure 16. ‘Hot spot’ map of all F3 tornados in Minnesota from 1997 to 2012.

Discussion

In 2012, there were 36 times the number of tornados recorded as recorded in 1950, an astounding difference. Joshua Wurman, president of the Center for Severe Weather Research, explains in an interview with Lamb (2010) that this is likely due to a combination of population growth and improvements to the technology used to detect and record tornados. Doswell (2007) also suggests the increase may be due to changes within the NWS. Regardless of the reason for the increase, the examination of the data using the Student’s t-test confirmed that the change in tornado activity in Minnesota is significant.

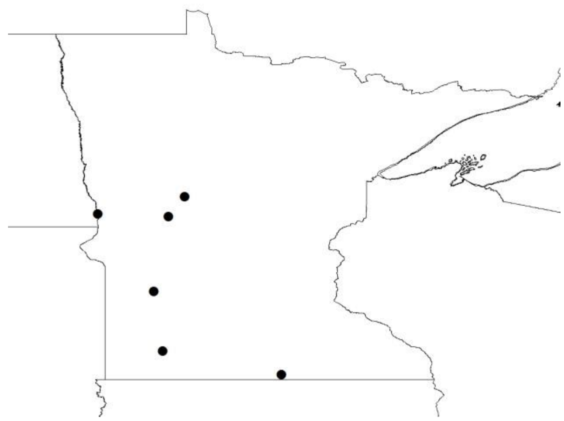

Figure 17. Locations of all F4 tornados in Minnesota from 1997 to 2012.

Table 3. Tornados by month at each latitude range from 1997-2012. The only tornado events north of the 49th parallel for this time period occurred in June or July.

Latitude	March	April	May	June	July	August	September	October	November
49.0-49.9	0	0	0	1	2	0	0	0	0
48.0-48.9	0	0	9	21	26	13	0	0	0
47.0-47.9	0	0	19	38	37	13	0	0	0
46.0-46.9	0	3	10	42	31	16	7	0	0
45.0-45.9	0	6	28	59	47	9	11	1	1
44.0-44.9	9	7	20	60	44	30	5	1	4
43.0-43.9	7	1	21	59	14	14	1	0	0

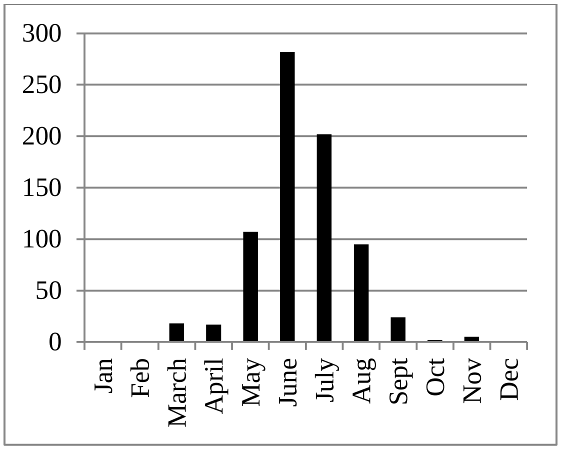

Figure 18. Total number of tornados by month for 1997 to 2012.

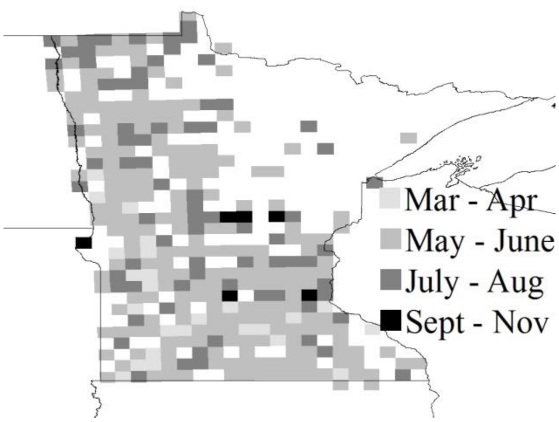

Figure 19. The earliest month a tornado was observed from 1997 to 2012. White space represents areas with no tornados over the time span.

Over this period the average intensity of recorded tornados has decreased (Figure 5). This is likely due to the under reporting of weaker tornados in the earlier years of the tornado record. Over time there has been an increase in the number of tornados recorded with lower F or EF ratings compared to the number of tornados recorded with higher ratings. The technological advances in tornado detection may account for much of the increase in the reporting of weaker tornados.

Tornado distribution across the state is not statistically uniform. Northeast and central Minnesota (regions 2, 3, 5 and 6) experience significantly fewer tornados than expected. This could be caused by the climatological effects of Lake Superior. Peaks in tornado frequency across the state occurred in regions 1, 4, 7 and 8 (Figures 3, 9 and 12). The Chi-Square analysis of tornados by region confirms that this uneven distribution of tornados across the state is highly significant. Minnesota experiences so few tornados with high F or EF ratings, it is inconclusive with this sample size if some parts of the state experience more intense tornados than others (F or EF rating of 3 or higher). Based on this limited sample, the southern half of Minnesota appears to be more susceptible to tornados with higher ratings (Figures 10, 11, 16, and 17).

The seasonal distribution of tornado events observed in this study of the 1997 to 2012 time period align very closely with the findings of the Minnesota Climatology Working Group (MNCWG) (2013) (Table 4). This indicates the 1997 to 2012 sample has a seasonality representative of the larger sample (1950 to 2012) studied by MNCWG. The distribution of tornados in Figure 19 and Table 3 indicate Minnesota experiences tornados at lower latitudes in the spring and the fall. This is likely tied to the timing of changes between seasons and the associated weather patterns. This would also explain why Minnesota experiences weather conditions favorable for tornados later in the season than states to the south. Table 3 shows only two tornados in October but five in November. This may be a glimpse at the "fall tornado season", as discussed in Doswell (2007).

Conclusions

Some factors contributing to the frequency and intensity of recorded tornados have changed since 1950. The most important may have been the completion of NEXRAD in the mid-1990s. This change contributed to the detection of less significant tornados and explains why the average annual tornado intensity plateaus during this time (Figure 5). A t-test confirmed a highly significant increase in tornado observations that coincided with the completion of NEXRAD. Based on the findings here, it is not reasonable to use the entire data sample from 1950 to 2012 to study trends in tornado frequency. Based on the findings here, there does not appear to be a true increase in tornado activity, but rather continual improvement in tornado detection. If there has been an increase in tornado activity it is lost in the non-environmental factors that contribute to fluctuations in tornado observations.

Table 4. Percent of tornados by month for this study (1997-2012) compared to the findings of the MNCWG (1950-2010) (2013).

Month	1997 – 2012 (%)	1950 – 2010 (%) (MNCWG)
Mar.	2.4	1
Apr.	2.2	4
May	14.2	15
June	37.5	37
July	26.9	25
Aug.	12.6	12
Sept.	3.2	4
Oct.	0.3	2
Nov.	0.7	0

Spatially, Minnesota experiences significantly more tornados in the south central and northwest regions of the state (regions 1, 4, 7, and 8 from Figure 3). And Minnesota experiences significantly fewer tornados in the northeast and central regions of the state (regions 2, 3, 5 and 6 from Figure 3). The southern part of the state experiences more intense tornados than the north. The northeast corner of Minnesota experiences almost no tornados compared to the rest of the state. This may be due to the proximity of Lake Superior, but more work is needed on the impact the "lake effect" has on the atmospheric conditions that form tornados.

The seasonal distribution of tornados in Minnesota from 1997 to 2012 is closely aligned with the average from 1950 to 2010 (Table 4). This means the 1997 to 2012 sample is representative of tornado seasonality in Minnesota. More work will be needed on this in the future, when there are more years of data to understand if the seasonal distribution shifts over time.

There is a lot to be learned from the continued study of Minnesota tornados. Minnesota is significant in the study of tornados because it experiences tornados later in the season than other states. The limited sample studied here suggests the northern part of Minnesota does not experience tornados as early or as late in the season as the southern part of the state. Further analysis is needed on the affect latitude and possibly altitude or land cover may have on these phenomena.

Acknowledgements

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