Indiana Tornado Climatology 1950-2010

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Abstract

The spring of 2011 showed that all efforts aside, forecasting a tornado's genesis, destructive potential, and duration is still a challenge facing forecasters and the public today. Identifying regions in the United States with a propensity for tornadic activity can help researchers explore why some regions appear more favorable for tornadogenesis than others and help forecasters and the communities in these regions to be more aware of areas with greater susceptibility to tornadic storms. With this motivation, a spatial tornado climatology was developed and analyzed for the state of Indiana from 1950-2010. Local "tornado alleys" are brought to light and compared to the spatial distribution of population and local geographical features. Findings suggest a possible population feedback to the number of tornado reports in individual counties; however, the signal is not strong enough to rule out local geographic features as possible contributors to regions of higher tornado activity.

1. Introduction

Efforts to identify active regions of severe weather and tornadogenesis have been completed a number of times over the last several decades. Tornado climatologies have been undertaken at different spatial and temporal scales. Locations include countries such as the United States, Austria, Germany, and the United Kingdom (Brooks et al. 2003; Doswell 2003; Holzer 2001; Dotzek 2001; Kirk 2007), and states such as Tennessee, Oklahoma, Iowa, and Indiana (Agee 1970; Beadle 1983; Branick 2001; Pryor and Kurzhal 1998; Rose 2004). Climatologies have explored annual trends, monthly/seasonal trends, days, nocturnal events, injuries, and fatalities (Agee 1970; Ashley 2007; Brooks et al. 2003; Concannon et al. 2000; Curran 2009; Dixon et al. 2011; Doswell 2003; Kis and Straka 2010; Rose et al. 2004; Schneider et al. 2004), and some climatologies explore the possible relationships between teleconnection patterns such as the El Niño Southern Oscillation and tornadoes (Agee and Zurn-Birkhimer 1998; Cook and Schaefer 2008; Mayes et al. 2007; Nunn and DeGaetano 2004; Rhome et al. 2000). Efforts of past research on tornado climatologies have also identified locations with higher numbers of tornadoes and the possible impacts of population on tornado spotting and reporting (Changnon 1982; Twisdale 1982; Tescon et al. 1983). Of recent concern to operational meteorologists, the media, and county emergency managers is the desensitization of the public to tornado warnings. A recent 5-year climatology of tornado false alarm rates shows how difficult it still remains to accurately detect and warn for a tornado (Brotzge et al. 2011), providing more persuasive evidence of a need to document, study, and apply noted trends in tornado frequencies and distributions across the United States.

Observations of tornadoes have occurred long before national databases began keeping official records. The first tornado ever photographed (August 1884) shows a tornado and two funnels approximately 20 miles southwest of Howard, South Dakota (Ross et al. 2001). South Dakota lies within an area of the United States recognized as “Tornado Alley,” defined by the Storm Prediction Center (Edwards 2011; and applied for use in this paper) due to higher risk in these states for strong and violent tornadoes (as adapted by Concannon et al. 2000). The region covers primarily Texas, Oklahoma, Kansas, Nebraska, southwest Iowa, eastern South Dakota, and eastern Colorado. However, the Midwest Great Lakes region (Wisconsin, Michigan, Illinois, Indiana, and Ohio), along with Kentucky sees a fair amount of tornadoes, having been struck in the past by tornadic events such as the 1965 Palm Sunday Outbreak and the 1974 Super Outbreak. In recent years, some national tornado climatologies have identified the Midwest Great Lakes Region as a branch or corridor extending from Tornado Alley, where an increase in tornado frequency is documented, more specifically through Illinois and into Indiana, especially when reviewed for strong (F2-F5) tornadoes (Agee and Zurn-Birkhimer 1998; Ashley 2007; Concannon et al. 2000; Dixon et al. 2011; Rauber et al. 2005). Tornado reports and tornado-day counts are not as high as those values found for classic Tornado Alley; however, the Midwest Great Lakes region and Kentucky are one of the other more active regions with higher numbers of tornado reports and tornado days documented.

Indiana is a state frequently affected by mid-latitude cyclones and associated atmospheric phenomena such as tornadoes. Tornadoes form in many environments and within different types of convection, all of which have been reported in Indiana: quasi-linear convective system tornadoes (50% of the state’s reported tornadoes: Trapp et al. 2005), supercell tornadoes, low-top mini supercell tornadoes, landspout tornadoes, and gustnadoes, as well as many tornado outbreaks (Agee and Jones 2009). Due to Indiana’s spatial location in relation to the strength and orientation of the jet stream along with the collision of arctic, continental, and subtropical airmasses, it makes the state an active location for all tornado types as listed above. While national climatologies show an increased frequency of tornadoes over the state, only two other climatologies for the state of Indiana have been completed (Agee 1970; Pryor and Kurzhal 1998). This climatology complements these past studies, and further explores population biases, and in a follow-up study, will explore the possibility of land surface interactions resulting in localized tornado alleys.

This Indiana tornado climatology reviews tornado storm report data (location, injuries, fatalities, F-scale) at annual, monthly, and hourly intervals, and "tornado-day" data at annual, seasonal, monthly, and 30-year climatological intervals. Indiana's population density is included in this study and possible regions of land surface interactions are noted to address the following questions: 1) What are the most active years, months, seasons, and hour of day for a tornado (and associated injuries and fatalities) in Indiana? 2) Does population density appear to play a role in the number of reported tornadoes in Indiana? 3) Does there appear to be a land surface feedback due to urbanization, and an increased frequency of tornadoes near significant land surface heterogeneity? 4) Has there been a noted increase in tornado reports and tornado days over time in Indiana?

The development of this climatology intends to provide updated insight to local meteorologists, emergency managers, and news media on when and where there is a greater likelihood for tornadoes in Indiana. The findings of this study will be conveyed to the public to heighten awareness of the tornado threat in Indiana. Noted trends in the seasonal and hourly distributions of tornadoes in Indiana will identify the more active times of year and day for tornadoes.

a. Tornadic Environments

Although tornadoes are most commonly reported in the months of May and June nationwide, tornadoes develop in several different atmospheric environments and throughout every season (Edwards 2011; Rauber et al. 2005). The environments in which tornadoes develop are largely impacted by the month in which they occur, as the orientation and strength of the jet stream and the amount of convective available potential energy (CAPE) available to sustain and fuel the updraft of the storm changes with the seasons and where the jet stream is located. In general, there are three typical environments that are conducive to tornadogenesis and are related to the climatology of storm-relative helicity (SRH), CAPE, and the jet stream: low CAPE, high SRH (spring and fall); high CAPE and high SRH (late spring and early fall); and high CAPE, low SRH environments (summer pulse-type storms that are more common in the southeastern United States or in regions with a weak upper-level disturbance and in the Midwest in mid to late summer; Doswell et al. 2001). Each environment generates a different type of storm dynamic that can affect subsequent tornadogenesis.

b. Tornadic Environment Increase or Population?

Recent years have seen a surge in many people's desire to become trained weather spotters. Convective wind, hail, and tornado reports increased greatly starting in the early 1990s when National Weather Service (NWS) efforts to increase storm spotter networks heavily increased, along with the advent of Doppler radar. Coupled with the increase in storm spotters in the last several decades is an increase in population around city centers and suburbia. This raises the question: are more tornadoes developing than before, or are more tornadoes just being spotted and reported because there are more people in proximity to where the tornado occurs (McCarthy 2003; McCarthy et al. 2006; McCarthy and Schaefer 2004; Ray et al. 2003)?

Basic methods of statistical analysis require datasets to have specific population threshold values (i.e., the size of the dataset population) to have results considered valuable. When reviewing the national records for tornado reports, the time frame of actual reports spans a mere 60 years. Although this record contains thousands of tornado reports, the quality of the 60-year data base is less than ideal. Doswell (2007) provides a good explanation on how storm report data are filled with uncertainties regarding the quality of data in the dataset. However, Doswell (2007) also notes that the dataset is all that meteorologists and researchers have to work with currently.

2. Datasets and Methodology

Several datasets were obtained and several datasets were generated for use in the development of this climatology: 1) the Storm Prediction Center (SPC) Warning Coordination Meteorologist (WCM) Severe Weather Database files from 1950-2010 (NCDC 2011); 2) SPC Severe Geographic Information System (SVRGIS) tornado track shape files for geospatial analysis (1950-2010); 3) NCDC Storm Event Database tornado counts by county (1950-2010); and 4) the development of a "tornado day" dataset from the SPC WCM Severe Weather Database files.

The geospatial dataset used for the development of this Indiana tornado climatology was obtained from the SPC SVRGIS database. All files are national datasets, thus, data needed for specific locations, such as specific states, had to be extracted. The "Tornado_Tracks" and "States" shapefiles were downloaded, added to a blank map document, and queried to extract and create a shapefile for the Midwest Great Lakes Region (previously defined) inclusive of Kentucky, with similar procedures for the development of shapefiles for just the state of Indiana, and Indiana counties and cities. The "Tornado_Tracks" shapefile, once implemented into

ArcGIS, was manipulated and queried for statistical analysis and interpretation in this study. The SPC also provides tornado storm report data which were analyzed. This was completed for the years 1950-2010 to study injuries, fatalities, and the most active time of day for tornadoes. Population counts were obtained from the 2009 United States Census county population estimates for Indiana. Population estimates per county were added to a database file and joined to the "Indiana_Counties" shapefile for mapping use and analysis.

a) ArcGIS Queries

Multiple queries were completed on the "Tornado_Tracks" shapefile to create the following shapefiles used for interpretation and analysis: Midwest F0-F5 tornadoes ("all"); Midwest F0-F1 tornadoes ("weak"); and Midwest F2-F5 tornadoes ("strong"), where the name "Midwest" is representative of the Midwest Great Lakes Region and Kentucky. Midwest tornado track shapefiles were used to spatially interpolate tornado track density images instead of just Indiana tornado tracks in order to provide continuity to the density map across state borders. The Midwest tornado track shapefiles were utilized to create density maps for all Indiana tornadoes, weak Indiana tornadoes, and strong Indiana tornadoes. The ArcGIS Spatial Analyst tool for line density was applied to each dataset to create a spatially interpolated shapefile from tornado track data revealing locations/areas in the state of highest and lowest tornado track densities. The raw tornado count for each county was determined via query from the NCDC Storm Events Database, entered into a database file, and also joined to the "Indiana_Counties" shapefile for mapping purposes.

b) ArcGIS Map Displays

ArcGIS allows for multiple types of spatial analysis for numeric datasets as related to a given location such as county, city, or a given latitude and longitude. The types of maps generated in this study are Choropleth maps in an Albers Equal Area Conformal Conic projection. Choropleth maps are thematic maps showing a quantity per unit area (typically at county, state, or country level). The tornado track density files generated for all, weak, and strong tornadoes are raster files that are "smoothed" to show continuous, interpolated data. The density display is plotted as a color gradient with the greater number of tornado tracks in a defined search radius as warmer colors and the least number of tornado tracks in a defined search radius as the coolest colors on the color ramp. The F-scale is used instead of the EF-scale because a majority of tornadoes in the NCDC database and all of the tornadoes in the SPC SVRGIS files are classified with F-Scale rankings.

3. Validity of Datasets

The SPC SVRGIS and NCDC Storm Event Database county tornado counts are used separately in the geospatial analysis because of inconsistencies between the SPC SVRGIS "Tornado_Tracks" shapefile (developed from Severe Weather Database files by the SPC) and the NCDC Storm Events Database tornado report information. Our assessment indicated that the SVRGIS shapefiles lack some tornado tracks when comparing tornado counts per county between NCDC Storm Events Database tornado counts by county and the attribute tables of the SVRGIS files. The GIS tornado track shapefiles also appear to incorrectly plot some tornado tracks. Therefore, the spatial *density* distribution maps generated in this study from the SVRGIS tornado track shapefiles represent a <u>*general*</u> spatial distribution pattern, <u>*not an exact*</u> density distribution pattern. The SPC WCM Severe Weather Database files were used to find the tornado frequencies for active years, months, time of day, injury, and fatality information. The SPC WCM Severe Weather Database files were also selected for use over the NCDC Storm Events Database injury and fatality information due to its ease of access for query as an already assembled spreadsheet. Please note though, that the SPC WCM Severe Weather Database files are compiled from NCDC's *Storm Data* database, so the datasets contain the same information. The NCDC Storm Events Database was queried for all, weak, and strong tornadoes by county, therefore any storm listed in the database by location (proximity to town/city) was pulled for the respective county of that location. Tornadoes that crossed county lines are counted as a tornado for a given county it entered; thus a tornado that traversed through three counties was counted as a tornado in each county.

4. Discussion of Findings

a. Storm Report Data

Storm report data are vital to understanding tornado frequency, location, occurrence, and duration of a severe event because they provide latitude and longitude locations, time of day, and date of the storm report. Often included in the dataset is the size and or intensity of the event being reported, which when compared to radar data provides insight into future forecasting and warning methods. Each reported tornado event includes information regarding location, time of day, tornado intensity/damage ranking, injuries, fatalities, and estimated cost of damage. The information provided by these numbers allows forecasters to be more aware of more active or suitable times of day, month, or year for tornado events, the likelihood of injuries, and the likelihood of fatalities within the state. Results of storm report analysis are discussed.

The annual occurrence of tornadoes according to storm report data in Indiana has no discernable upward or downward trend for the duration of the dataset. The averages and standard deviations have been rounded. Data are presented in a tabular format for ease of analysis (Table 1). Figure 1 (A-C) show bar graphs of total annual storm reports for all, weak, and strong tornadoes.

(a) Years with Tornado Storm Reports for F0-F5 Tornadoes 1 SD above Average		
1965	1976	1992
1973	1980	1998
1974	1990	2004

(b) Years with Tornado Storm Reports for F0-F1 Tornadoes 1 SD above Average		
1973	1990	2004
1976	1992	2006
1980	1996	2008
1989	1998	2010
	2003	

(c)Years with Tornado Storm Reports for F2-F5 Tornadoes 1 SD above Average		
1956	1965	1990
1961	1967	1992
1963	1974	

(d) Years Listed in at least 2 of the Previous 3 Tables		
1973	1990	2004
1976	1992	
1980	1998	

Table 1 (a-d): Active tornado years for all tornadoes (a), weak tornadoes (b), and strong tornadoes (c) defined by having the total number of tornado storm reports one standard deviation above the mean, 1950-2010. Years that are listed in a least two of tables (a), (b), and (c) are listed in (d).

The monthly distribution of Indiana tornadoes shows that the most active months (in descending order) for tornadoes are June, April, and May. The least active months are December, January, and February (Figure 2A). The most active months for weak tornadoes (in descending order) are June, May, and April (Figure 2B). The strong tornado dataset monthly distribution shifts slightly (Figure 2C), with the most active month being April, followed by June, and then March (most likely skewed by the 1965 Palm Sunday Outbreak and 1974 Super Outbreak). A seasonal trend is apparent, with Indiana having two tornado seasons: spring into summer, and then a secondary, short-lived season in the fall (October and November).

Injuries and fatalities in Indiana have occurred for both weak as well as strong tornadoes. Fatalities and injuries due to weak tornadoes are typically attributed to the structure in which the individual was seeking shelter at the time of the event. Most injuries and fatalities associated with weak tornadoes have been reported in mobile or sectional homes. The annual distribution for all tornado injuries places the years of 1965 and 1974 as top years (which are years of the "Palm Sunday" and "Super Outbreak," respectively). For weak tornadoes, injuries were greatest in the years of 1975, 1990, 1993, 1995, 2001, and 2004. For strong tornadoes, the most active years in terms of injuries are 1965 and 1974 which again shows the direct relationship to outbreak events.

The three most likely months for an individual to be injured by a tornado in Indiana in descending order are April, November, and June. The most likely months to be injured from a weak tornado in Indiana are also the months of April, November, and June. Strong tornadoes are most likely to injure people in the months of April, November, and June as well; however the month of April is, by far, the most likely month to be injured by a strong tornado. November is prominent in the dataset because of the 20+ fatalities from the Evansville tornado in 2005.

The annual distribution of fatalities for all tornadoes is heavily impacted by tornado outbreak events. Of these 1965, 1974, and 2005 (in descending order) are the three deadliest years for tornadoes, which again are the years of the Palm Sunday Outbreak (April 11, 1965), the Super Outbreak (April 3-4, 1974), and the Evansville tornado (November 6, 2005), respectively. The distribution of fatalities for weak tornadoes encompasses several more years: 1963, 1971, 1976, 1977, 1980, and 2008. Strong tornado fatalities are once again determined by outbreak years of 1965, 1974, and the Evansville tornado.

April, November, and June are the deadliest months for all Indiana tornadoes. Weak tornadoes have been most deadly in the months of January (one fatality), March, May, and October (one fatality). April, November, and June are the deadliest months for Indiana regarding strong tornadoes. Once again, these statistics are heavily impacted by outbreak events and night events when people are less likely to receive or respond to advance warning.

Further analysis of injuries and fatalities was completed regarding injuries by F-scale classification. Sixty-three percent of all injuries from Indiana tornadoes are a result of F4 tornadoes, followed by F3 tornadoes (19%), and F2 (8%). Fatality statistics reveal similar trends, with 71% of fatalities attributed to F4 tornadoes, followed by F3 tornadoes at 20%, and F2 at 3%. Table 2 shows time of day information related to injuries and fatalities.

Most Active Time of Day for Tornadoes

	All (F0-F5)	Weak (F0-F1)	Strong (F2-F5)
Hour	2:00-8:00 PM LST	3:00-7:00 PM LST	2:00-9:00 PM LST

Most Active Time of Day for Injuries

	All (F0-F5)	Weak (F0-F1)	Strong (F2-F5)
Hour	3:00-6:00 PM LST	3:00-7:00 PM LST	3:00-6:00 PM LST

Most Active Time of Day for Fatalities

	All (F0-F5)	Weak (F0-F1)	Strong (F2-F5)
Hour	5:00-7:00 PM LST & 1:00-2:00 AM LST	7:00-11:00 AM & 3:00-7:00 PM LST	5:00-7:00PM LST & 1:00-2:00 AM LST

Table 2: Daily, temporal distribution of tornadoes, injuries and fatalities. The most active time of day for tornadoes in Indiana falls into the national most active times of day, 2:00 pm LST – 7:00 pm LST, as found in Rauber et al. (2005).

b. "Tornado Day" Data

"Tornado day" data are ideal to compare to storm report data because that removes multiple reports of the same tornado or storm, which highly skews the dataset. A "tornado day" is modeled after Changnon and Schnickedanz (1969) and equates a tornado day as a day with at least one tornado report. This removes the bias of multiple reports for the same tornado and provides an idea of how many days are favorable for tornadogenesis in a given year and month across Indiana. Analysis of tornado-day data was completed to find the average number of annual tornado days from 1950-2010 for all three datasets (all, weak, and strong), along with 30-year climatologies to determine if averages have increased or decreased over time. Monthly averages of tornado days for all, weak, and strong tornadoes, were also determined. Results are discussed in the following paragraphs.

For all tornadoes, the average number of tornado days per year is nine. Years with tornado counts one standard deviation greater than the average are listed in the table below and in Figure 3A. The peak months in Indiana for tornado days are June, May, and July (descending order) with the least active months being December, January, and February (Figure 3B). Thirty-year climatologies are listed in Table 3 show little variation through time with only a slight bias towards the early periods.

(a) Years with F0-F5 Tornado Days 1 SD above Average	
1954	1978
1961	1998
1973	2003
1975	

(b) 30-Year Climatologies F0-F5	
Years	Ave. # Tornado Days
1950-1980	10
1960-1990	9
1970-2000	9
1980-2010	8
1950-2010	9

Table 3 (a-b): (a) Years with number of tornado days one standard deviation or greater than the dataset mean 1950-2010. (b) 30-year tornado day averages 1950-2010. Average number of tornado days a year for all tornadoes has seen little change.

On average, there are seven tornado days per year conducive to weak tornadogenesis in Indiana. Years with weak tornado days one standard deviation greater than the average are listed in the table below and in Figure 3C. Thirty-year climatologies shown in Table 4 once again show little variation through time. Monthly tornado-day data show that weak tornado days for Indiana are most common during the months of June, May, and July (in descending order). The least active months in terms of tornado days are December, January, and February (Figure 3D). Weak tornado days were determined by sorting out F0 and F1 tornadoes and then counting the number of days--which means that it is possible for a weak tornado day to also be a strong tornado day and vice versa.

(a) Years with F0-F1 Tornado Days 1 SD above Average	
1954	1996
1973	1998
1975	2003
1978	2006
1992	2008

(b) 30-Year Climatologies F0-F1	
Years	Ave. # Tornado Days
1950-1980	7
1960-1990	7
1970-2000	8
1980-2010	8
1950-2010	7

Table 4 (a-b): same as Table 2 except for weak tornadoes.

Years with strong tornado-day totals greater than one standard deviation above the mean are listed in Table 5 and in Figure 3E. The average number of tornado days for strong tornadoes from 1950-2010 is three per year. Thirty-year climatologies, shown in Table 4, indicate a fairly significant decrease in the number of tornado days in recent years compared to early years. When reviewing strong tornadoes over time (1950-2010), tornadoes in a monthly distribution by tornado day show June as the most active month. The second most active month in terms of tornado-day classification is April, followed by the month of May. The least active months are December, January, and February (Figure 3F).

(a) Years with F2-F5 Tornado Days 1 SD above Average	
1954	1962
1956	1963
1957	1965
1958	1967
1960	1968
1961	1980

(b) 30-Year Climatologies F2-F5	
Years	Ave. # Tornado Days
1950-1980	5
1960-1990	4
1970-2000	2
1980-2010	2
1950-2010	3

Table 5: Same as table 2 and 3 except for strong tornadoes.

c. Map Data

ArcGIS 9.3 was used to develop the population and tornado spatial distribution maps discussed in the following paragraphs. Maps were generated to analyze the spatial distribution of all tornadoes, weak tornadoes, and strong tornadoes as related to the United States Census Bureau 2009 county population estimates for the state of Indiana. Land surface features in the state of Indiana such as locations downwind of urban areas, large changes in elevation, and substantial shifts in land cover are briefly noted.

1) POPULATION DISTRIBUTION

The 2009 population estimates for each county were broken into three datasets and used in maps and tables for analysis: a normalized population, raw population count, and population density per square mile. Table 6 A-D (end of paper) shows the twenty highest- and twenty lowest-ranking counties for population density per square mile and the twenty highest- and lowest-ranking counties in terms of number of standard deviations the total population estimate is from the population mean. The two lists of twenty highest- and twenty lowest-ranking counties were then compared to the counties with the top twenty highest and lowest tornado counts.

Counties that fall in all three population datasets (raw estimate, not within 0.5 to -0.5 of mean, and population density) for the highest population values are: Allen, Elkhart, Hamilton, Marion, Lake, Vanderburgh, Porter, Johnson, and St. Joseph. Crawford, Martin, Benton, and Warren are the only counties of the lowest populated counties that fall into all three dataset classifications. The counties that fall in the list of highly populated counties are home to large cities and metropolitan areas where numerous people reside. Lake County is home to Gary and Chicago suburbs; Marion County is home to Indianapolis; St. Joseph County is home to the city of South Bend; Allen County is home to the city of Ft. Wayne; Elkhart County is home to the cities of Elkhart and Goshen; Hamilton County contains the cities of Fishers and Carmel and is one of the fastest growing counties in the state; Vanderburgh County is home to the city of Evansville; Porter County lies east of Lake County and is also heavily influenced by the presence of Chicago suburbs, and the city of Valparaiso; and Johnson County is home to the Indianapolis suburbs of Greenwood and Whiteland.

Crawford, Martin, Switzerland, Benton, and Warren Counties are the least populated counties by all three population datasets. Crawford County lies along the Ohio River with no major cities; Martin County is covered by the Hoosier National Forrest and Crane Naval Base with small town and cities, but no large population centers; Switzerland County also resides along the Ohio River with minimal towns and cities; Benton and Warren Counties both lie in the northwest portion of the state, making up part of Indiana's western border with Illinois. Both counties are mainly rural with no large cities serving as population centers.

2) TORNADO DISTRIBUTION

Tornadoes have occurred in every county in Indiana; however, some counties have reported substantially more tornadoes than others. A spatial distribution of reported tornado paths and a density distribution of these tracks show distinctive regions in Indiana with more tornado activity than others (Figure 4A). Tornado data as obtained from NCDC were broken into three datasets: total tornadoes, weak tornadoes, and strong tornadoes. These datasets were then mapped via Choropleth mapping (Figures 4B, 4C, and 4D, respectively) by number of tornadoes/tornado tracks per county and sorted to find the top twenty counties with the highest and lowest tornado counts for each dataset.

The top five counties with the greatest number of documented tornadoes and least amount of documented tornadoes are listed in Table 7 for all tornadoes, weak tornadoes, and strong tornadoes with Figure 4 (B-D) providing maps of the complete data:

Counties with the Highest Tornado Counts 1950-2010 All Tornadoes	
County	**Count**
Marion	41
Tippecanoe	38
Elkhart	32
Shelby	29
Allen, Boone	26

Counties with the Highest Tornado Counts 1950-2010 Weak Tornadoes	
County	**Count**
Marion	27
Tippecanoe	24
Elkhart	22
Allen	21
Hamilton	19

Counties with the Highest Tornado Counts 1950-2010 Strong Tornadoes	
County	**Count**
Shelby	17
Marion, Tippecanoe	14
Hancock	13
Boone	12
Elkhart, Henry, Knox, Lake	11

Counties with the Lowest Tornado Counts 1950-2010 All Tornadoes	
County	**Count**
Clay, Franklin, Martin	7
Switzerland, Crawford, Fountain	6
Brown, Floyd	5
Blackford	4
Ohio, Union	2

Counties with the Lowest Tornado Counts 1950-2010 Weak Tornadoes	
County	**Count**
LaGrange, Fountain, Sullivan	5
Franklin, Jefferson, Switzerland, Brown, Perry, Martin,	4
Fayette, Floyd, Crawford	3
Blackford, Scott, Ohio	2
Union	0

Counties with the Lowest Tornado Counts 1950-2010 Strong Tornadoes	
County	**Count**
Switzerland, Floyd, Posey	2
Orange, Union, Owen, Blackford	2
Whitley, Fountain, Parke	1
Brown, Green	1
Ohio, Spencer, Clay	0

Table 7: Counties with the five highest tornado counts for all, weak, and strong tornadoes (top row) and counties with the five lowest tornado counts for all, weak, and strong tornadoes (bottom row) 1950-2010.

It is apparent with the development of separate datasets for all tornadoes, weak tornadoes, and strong tornadoes that county rankings for assigned tornado frequencies shift. Classification of tornadoes prior to 1974 to the F-scale was completed through newspaper articles and pictures by researchers in the Technique Development Unit at the National Severe Storms Forecast Center, leading to a subjective and remote analysis of actual damage attributing to possible incorrect F-scale rating and too many strong tornado reports (Doswell 2007; McCarthy 2003; McCarthy et al. 2006; Ray et al. 2003). The implementation of Doppler radar has allowed for more accurate warning and verification of reports, especially for weak tornadoes (McCarthy

2003; McCarthy et al. 2006); however, the subjective nature of tornado damage classification by NWS personnel generates continued uncertainty in EF-scale damage classification. A map of strong-tornado track density for years 1974-2010 was completed to assess the spatial distribution pattern shift (Figure 5).

3) POPULATION AND TORNADO DISTRIBUTIONS

Multiple studies in recent years have shed light on the influence of population on tornado spotting and reporting by increased involvement of storm spotters (Anderson et al. 2007; McCarthy 2003; McCarthy et al. 2006). There is a working, general understanding that the more (less) people in a given area, the more (less) people are likely to see and report a tornado (Anderson et al. 2007). This Indiana tornado climatology takes a simple approach to assessing the impacts of Indiana's population distribution on past tornado spotting and reporting. It is completed with total tornado counts/tornado tracks per county, weak tornadoes counts/tornado tracks per county, and strong tornado counts/tornado tracks per county 1950-2010.

Recalling from the previous section, counties ranked in the top twenty most populated counties, the top twenty most densely populated counties, and counties greater than 0.5 standard deviations above the population mean are Marion, Lake, Vanderburgh, Hamilton, St. Joseph, Allen, Johnson, Elkhart, Porter, Hendricks, Tippecanoe, Monroe, and Madison Counties. Counties having populations 0.5 or more standard deviations below the mean are Crawford, Newton, Martin, Warren, and Benton Counties. Top-twenty lists for the most densely populated and least densely populated counties, along with a top twenty-list for the highest and lowest number of standard deviations a county lies above or below the mean, were generated and compared to the top twenty most active and least active counties for all tornadoes, weak tornadoes, and strong tornadoes (Table 6, end of paper). Maps of weak and strong tornado densities with highlighted counties of population outliers are shown in Figures 6A and 6B. A Choropleth map of population density and labeled county tornado count is provided in Figure 7A, and complemented by a Choropleth map of county tornado track count with the top twenty most populated counties highlighted in Figure 7B.

The correlation coefficients for all 92 counties' 2009 population estimates and the total, weak, and strong tornado counts per county (from here on PopTOR), along with all 92 counties' population densities and the total, weak, and strong tornado counts per county (from here on PDTOR) were found to analyze the degree to which population plays on tornado reporting in Indiana. PopTOR's correlation coefficient for all tornadoes is 0.63 and PDTOR's correlation coefficient is 0.59. While these correlation coefficients are positive and supportive to prior suggestions that a higher concentration of people in a given area will yield a greater likelihood of a tornado being spotted, the signal in the dataset is not strong enough to draw definitive conclusions regarding this claim for tornado distributions in Indiana. The correlation coefficient was also found for tornado days (TD) per county for all tornadoes and the two datasets of county population estimate and county population density (PopTORTD and PDTORTD, respectively). Values are similar to those found with the other two datasets. However, PopTORTD and PDTORTD have slightly lower correlation coefficient values at 0.57 and 0.56, respectively.

Alternative models were developed to further question the direct linear relationship between population and documented tornadoes. These models include a polynomial model, a logarithmic model, and a power model. Because some counties have zero reported tornadoes in the "weak" and "strong" datasets, only total (F0-F5) tornado counts could be used to generate a power-based model of tornado distributions and population density and population estimates. No model is suggestive of an accurate representation of tornado predictability regarding population. All models generate the highest correlation coefficients for population estimates and all tornadoes, and the lowest values for population density and strong tornadoes. Strong tornadoes have the lowest correlation coefficients most likely because they occur much less frequently than weak tornadoes, but are being compared to the same values of population and population density (Table 8, end of paper).

From this basic county tornado count for 1950-2010 as compared to 2009 population estimates, there appears to be a relationship between tornado counts per county and county population. While several counties listed as the most active for overall tornado count also make the list of most populated counties, there are some counties in the dataset that contain higher tornado reports and have a lower population (Shelby, Rush, and Hancock Counties). It is important, however, to consider the number of tornadoes reported in these counties prior to 1974 when damage rankings were determined via pictures. Recall the bull's-eye of greater F2 and higher tornadoes southeast of Indianapolis (Figure 4A). Half of Hancock, Henry, and Shelby Counties' tornadoes F2 and greater occurred prior to 1974 indicating that tornado damage may have been misclassified due to the procedure by which tornadoes were reviewed after the implementation of the F-scale. However, a map of F2 and greater tornadoes after 1974 (Figure 5) show that a bull's-eye region is still present in these counties, suggestive of possible land surface or urban heat island feedbacks because of lower county populations. It is occurrences such as these that raise additional questions regarding the spatial distribution of reported and documented tornadoes in Indiana.

Noted studies over land surface interactions to convection across multiple spatial and temporal scales leads to the question: is there a possible land surface feedback occurring in Indiana that is impacting tornado distribution, or is it indeed a factor of how scientists have studied and documented tornadoes over the years? Indiana does have two major land-cover transition zones close to regions of enhanced tornadic activity: 1) forested hills of southern Indiana to flat farmland on the till plains and 2) larger, relatively urban areas such as Lafayette, Ft. Wayne, Indianapolis, and South Bend to rural farmland. Other research shows that boundary layer feedbacks from land-cover transition zones that differ in latent and sensible heat fluxes can generate or enhance convection given certain background synoptic conditions (Baidya and Avissar 2000; Clark and Aritt 1995; Gopalakrishnan and Avissar 2000; Pielke 2001; Niyogi et al. 2006, 2011). Similarly, could Indiana’s landscape have an impact on storm morphology to favor tornadogenesis in some regions over others? A detailed analysis of Indiana’s land surface feedbacks to the boundary layer and tornadic storms is beyond the scope of this paper and will be reviewed in a subsequent study.

5. Conclusions

Tornado data from 1950-2010 as obtained from the SPC WCM Storm Report Data and the NCDC Storm Event Database reveal beneficial forecasting information on the temporal and spatial distribution of tornadoes across Indiana. The most active years, months, and time of day have been noted in this study and GIS-based maps were generated to show the spatial distribution of tornadoes across Indiana. Results show that population distribution appears to have an influence on tornado distribution across the state, but attention is still brought to other possibilities of increased tornado activity such as land/surface interactions, especially near urban and rural landscape transition zones.

Tornadoes are most active in Indiana during the months of April, May, and June, with June being the most active month for tornado reports and “tornado days” despite some of the most memorable outbreak events occurring in the earlier months of spring when the synoptic environment has strong SRH and the mean storm track of extratropical cyclones is oriented such that events in the Midwest are more likely (Whittaker and Horn 1981). Active years span the entire timeframe of the dataset, showing no apparent increasing or decreasing trend in the number of tornado days per year in Indiana. The average number of tornado days for strong tornadoes appears to be slightly decreasing when reviewed via 30-year average values. The average number of strong tornado days per year for 1950-1980 was five, decreasing to an average of two days a year for 1980-2010. The average number of tornado days per year for weak tornadoes for 1950-1980 was seven, increasing to an average of eight days per year for 1980-2010. The average number of tornado days per year for all tornadoes for 1950-1980 was 10, decreasing to an average of eight days a year for 1980-2010. When reviewing injury and fatality information, outbreak events sway the dataset showing one is more likely to be harmed by a tornado in early spring and in the fall (when SRH is higher, favoring stronger tornadoes), and one is more likely to be harmed by a tornado after dark than during the day. It is possible that fatalities which occur during "off-season" months occur because many people may not pay attention to the threat of an active tornado warning when outside of the normal tornado season. The most active time of day for tornadoes to occur in Indiana are between the hours of 2:00 pm LST and 8:00 pm LST. This time of day is when peak heating occurs and the greatest instability is generally present, and forecasters are typically prepared for an elevated tornado risk. The deadliest time of day according to tornado report data are the hours of 5:00 pm-7:00 pm LST and 1:00 am-2:00 am LST. It should not be assumed that these are the only times one should be concerned with tornadic development. Rather, forecasters need to be aware of all severe weather environments regardless of time of day and time of year to issue timely warnings and save lives and property.

The spatial analysis of the climatology agrees with findings by Ashley (2007), Concannon et al. (2000), and Dixon et al. (2011). There are pronounced areas through central Indiana that show locales of enhanced tornado occurrences. Results from this study place the axis of elevated tornado occurrences extending from Tippecanoe County east and southeast towards Indianapolis where a pronounced region of tornadic activity is present in eastern Marion County, and all of Hancock, Shelby, and Rush Counties. The axis then shifts to a more southerly orientation traversing southward through a narrow, central portion of the state The spatial location of tornado hotspots in the northern portion of the state can be largely attributed to outbreak events, where as the central Indiana axis of enhanced tornado activity is influenced by a larger variety of tornado events.

Population is shown in this study through moderate correlation coefficient values for the SDTOR and PDTOR datasets to play a role in the number of tornadoes reported in each county for the state of Indiana. Therefore, while it may be concluded that population distribution appears to play a role in the recorded number of tornadoes in Indiana, it is not the only contributing factor to the spatial distribution of tornado reports. Several counties in Indiana that rank in the top twenty most active counties actually have lower populations (Hancock County, Shelby County, and Rush County), all of which happen to be downwind of Indianapolis (given typical boundary layer winds in severe weather scenarios), a large feature that interrupts surface flow. Recent assessment of urban thunderstorms over the Indianapolis region (Niyogi et al. 2011) shows a possible relationship between urban landscapes and thunderstorm structure and lifecycles, coincidently where tornado hotspots are found in this study (Figures 8A and 8B). Future research will explore the possible land surface feedback and tornadogenesis downwind of urban areas in more detail.

This tornado climatology for Indiana was completed to provide forecasters and researchers up-to-date documentation on the annual, seasonal, and temporal distribution of tornadoes in Indiana and is complemented by a population study to determine possible causes influencing the spatial distribution of tornadoes in Indiana. Future studies regarding the potential role of land surface heterogeneities on tornado climatology needs to be completed.

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County	# of SD from Population Mean	County	Tornado Count (All)
Marion	7.10	Marion	41
Lake	3.67	Tippecanoe	38
Allen	2.46	Elkhart	32
Hamilton	1.81	Shelby	29
St. Joseph	1.71	Allen	26
Elkhart	1.13	Boone	26
Vanderburg	0.92	Hamilton	25
Tippecanoe	0.85	St. Joseph	25
Porter	0.81	Hendricks	25
Johnson	0.62	Kosciusko	24
Hendricks	0.62	Madison	23
Madison	0.54	Lake	22
Monroe	0.53	La Porte	22
Delaware	0.40	Marshall	22
La Porte	0.36	Knox	22
Clark	0.33	Porter	21
Vigo	0.32	Hancock	21
Howard	0.12	Henry	21
Kosciusko	0.06	Morgan	20
Bartholomew	0.06	Grant	20

A)

County	Pop. Density	County	Tornado County
Marion	2248.28	Marion	41
Lake	994.43	Tippecanoe	38
Vanderburg	747.9	Elkhart	32
Hamilton	701.83	Shelby	29
St. Joseph	585.15	Allen	26
Allen	538.44	Boone	26
Johnson	441.93	Hamilton	25
Elkhart	432.29	St. Joseph	25
Porter	391.28	Hendricks	25
Hendricks	344.29	Kosciusko	24
Tippecanoe	336.07	Madison	23
Monroe	331.53	Lake	22
Delaware	292.89	La Porte	22
Madison	290.66	Marshall	22
Clark	289.66	Knox	22
Howard	282.85	Porter	21
Vigo	262.76	Hancock	21
Hancock	223.23	Henry	21
Bartholomew	186.96	Morgan	20
La Porte	185.65	Grant	20

B)

County	# SDs from Population Mean	County	Tornado Count
Carroll	-0.43	Scott	10
Orange	-0.43	Jay	10
Perry	-0.44	Warren	10
Rush	-0.45	Sullivan	9
Parke	-0.45	Fayette	8
Fountain	-0.45	Spencer	8
Vermillion	-0.46	Orange	8
Tipton	-0.46	Perry	8
Brown	-0.47	Parke	8
Newton	-0.48	Clay	7
Pulaski	-0.48	Franklin	7
Blackford	-0.49	Martin	7
Pike	-0.49	Fountain	6
Crawford	-0.51	Crawford	6
Martin	-0.51	Switzerland	6
Switzerland	-0.51	Floyd	5
Benton	-0.51	Brown	5
Warren	-0.51	Blackford	4
Union	-0.54	Union	2
Ohio	-0.55	Ohio	2

C)

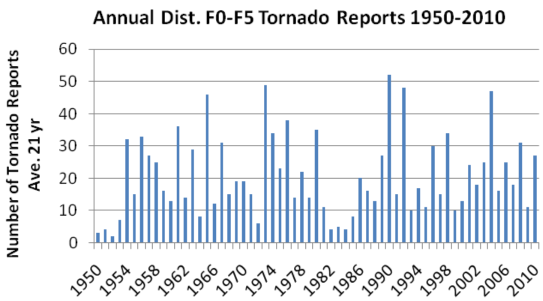
County	Population Density	County	Tornado Count
Washington	53.9	Scott	10
Carroll	53.06	Jay	10
Spencer	50.26	Warren	10
Perry	49.32	Sullivan	9
Orange	48.96	Fayette	8
Sullivan	47.3	Spencer	8
Brown	46.59	Orange	8
White	46.42	Perry	8
Switzerland	43.74	Parke	8
Union	43.58	Clay	7
Fountain	42.59	Franklin	7
Rush	42.07	Martin	7
Parke	37.99	Fountain	6
Pike	36.47	Crawford	6
Crawford	34.48	Switzerland	6
Newton	34.18	Floyd	5
Pulaski	31.39	Brown	5
Martin	29.59	Blackford	4
Warren	23.27	Union	2
Benton	21.2	Ohio	2

D)

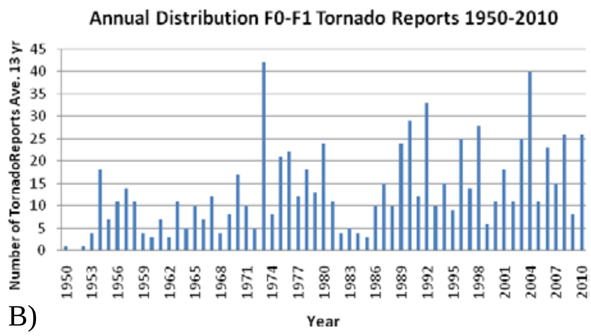
Table 6 (A-D): A) 2009 Indiana est. population twenty highest counties by number of SD from population mean vs. twenty highest total tornadoes per county (1950-2010). **B)** 2009 Indiana twenty highest county est. pop. density vs. twenty highest total tornadoes per county (1950-2010.) **C)** 2009 Indiana est. population twenty lowest counties by number of SD from population mean vs. twenty lowest total tornadoes per county. **D)** 2009 Indiana est. pop. density twenty lowest Counties vs. twenty lowest total tornadoes per county

	Linear	3rd Order Poly.	Logarithmic	Power
PD All (F0-F5)	0.59	0.68	0.65	0.55
PD Weak (F0-F1)	0.58	0.65	0.60	X
PD Strong (F2-F5)	0.42	0.51	0.52	X
Pop. All (F0-F5)	0.63	0.76	0.77	0.72
Pop. Weak (F0-F1)	0.63	0.74	0.73	X
Pop. Strong (F2-F5)	0.44	0.55	0.58	X
PDTORTD All (F0-F5)	0.56	0.73	0.54	0.46
PopTORTD All (F0-F5)	0.57	0.72	0.62	0.61

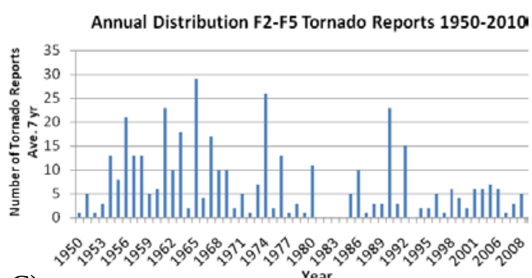
Table 8: Correlation coefficient for population density and county population for all, weak, and strong tornadoes per county (PDTOR and PopTOR), along with the correlation coefficient for population density and county population for tornado days (PDTORTD and PopTORTD) as found with a linear model, a third order polynomial model, a logarithmic model, and a power model. Spaces marked with an "x" indicate value could not be determined due to a zero in the dataset.



A)



B)



C)

Figure 1: A) 1950-2010 annual distribution of tornado reports. B) 1950-2010 annual distribution of weak tornado reports. **C)** 1950-2010 annual distribution of strong tornado reports.

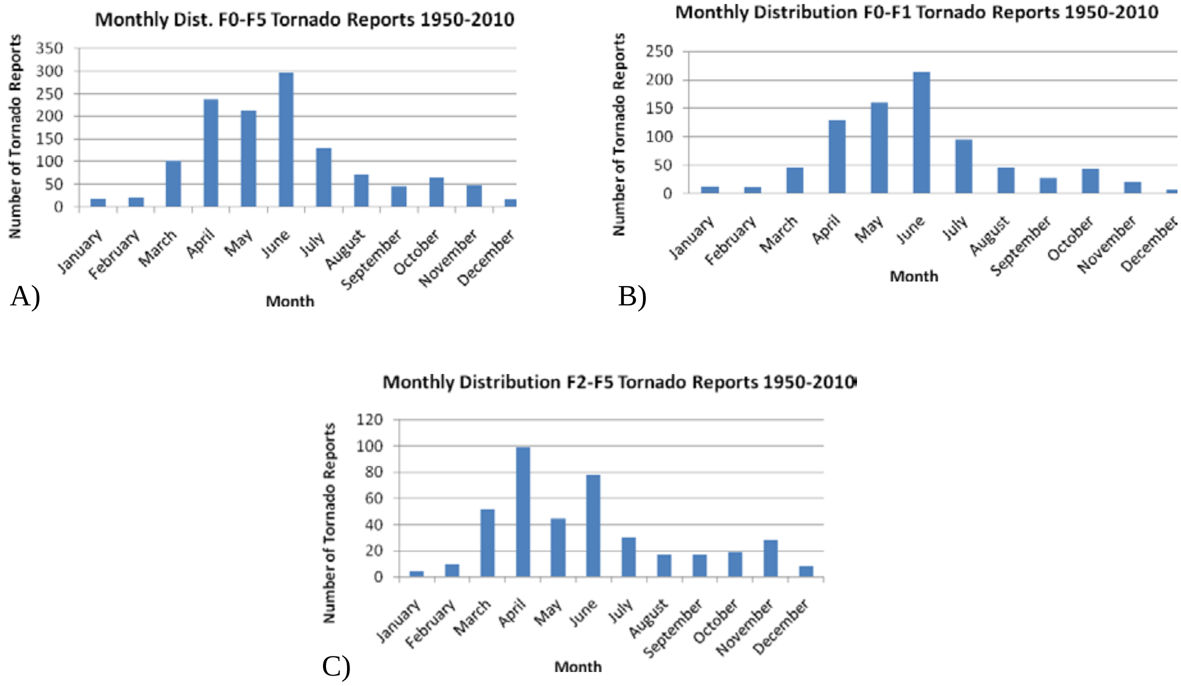


Figure 2: A) Monthly distribution of tornado reports for 1950-2010. B) Monthly distribution of weak tornado reports for 1950-2010. C) Monthly distributions of strong tornado reports for 1950-2010.

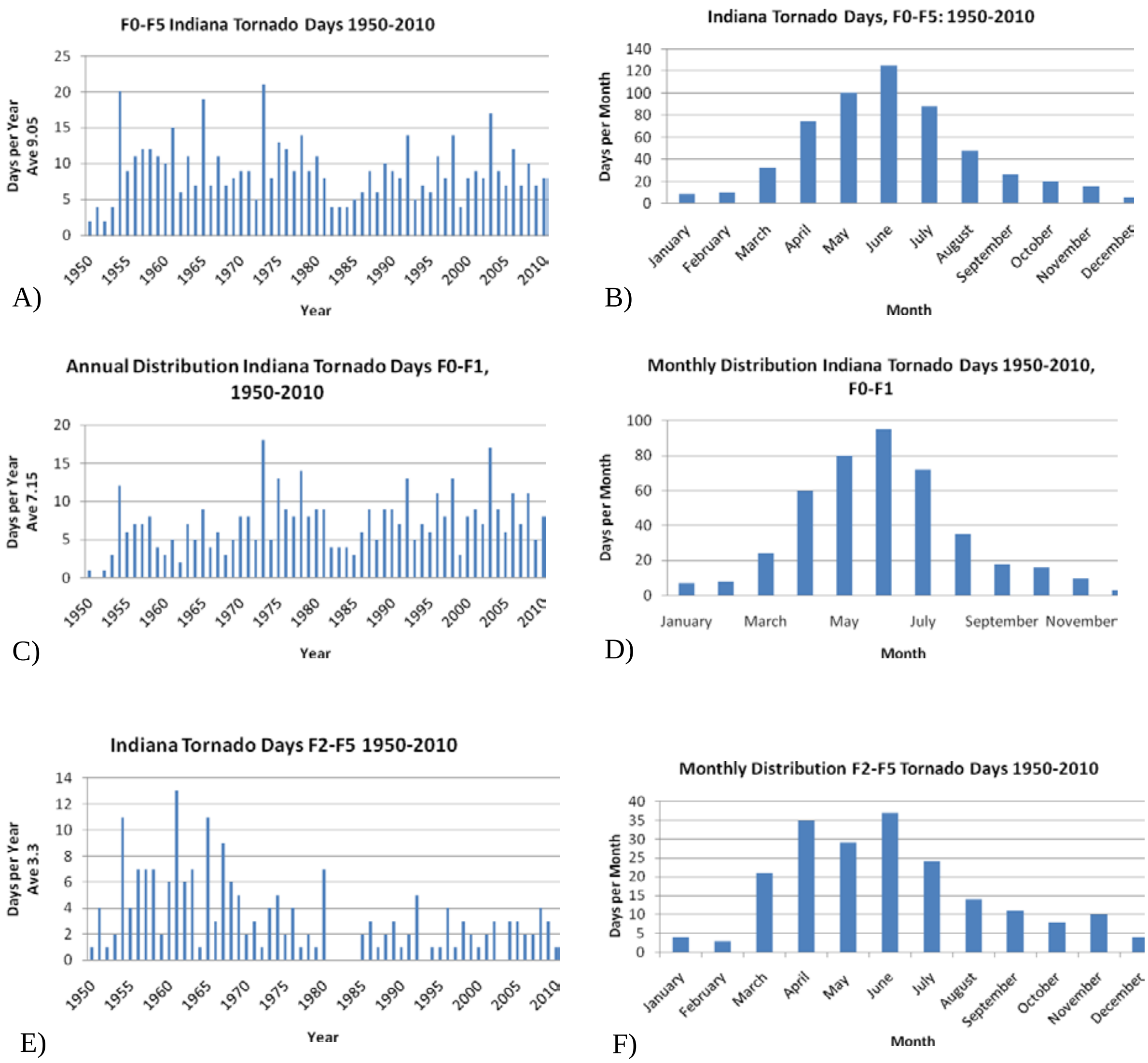


Figure 3: A) Annual tornado days for 1950-2010. B) Monthly tornado days for 1950-2010. C) Annual tornado day distributions for weak tornadoes for 1950-2010. D) Monthly tornado day distributions for weak tornadoes for 1950-2010. E) Annual distribution for strong tornado days for 1950-2010. F) Monthly distribution for strong tornado days for 1950-2010.

Figure 4: A) Track density map for all tornadoes for 1950-2010. B) Choropleth map of tornados per county for 1950-2010. Warm colors show counties with the highest tornado counts and cool colors with the lowest tornado counts. C) Choropleth map of Indiana counties classified according to number of weak tornadoes per county. Warm colors are counties with the highest tornado counts and cool colors are counties with the lowest tornado counts. D) Choropleth map of strong tornado tracks per county. Warm colors indicate counties with the highest amount of tracks and cool colors indicate counties with the lowest number of tracks.

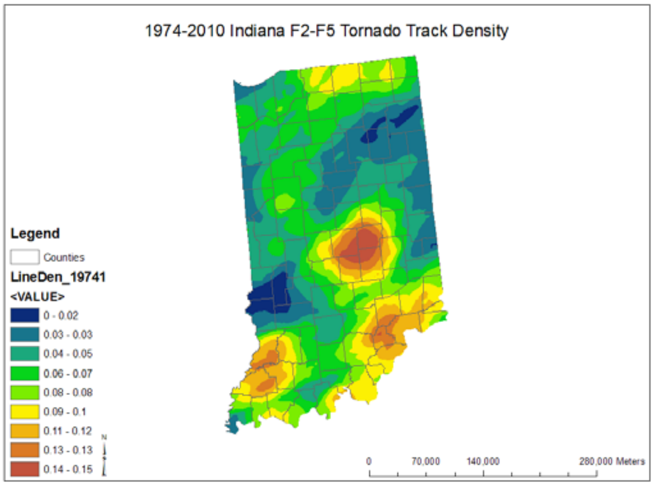
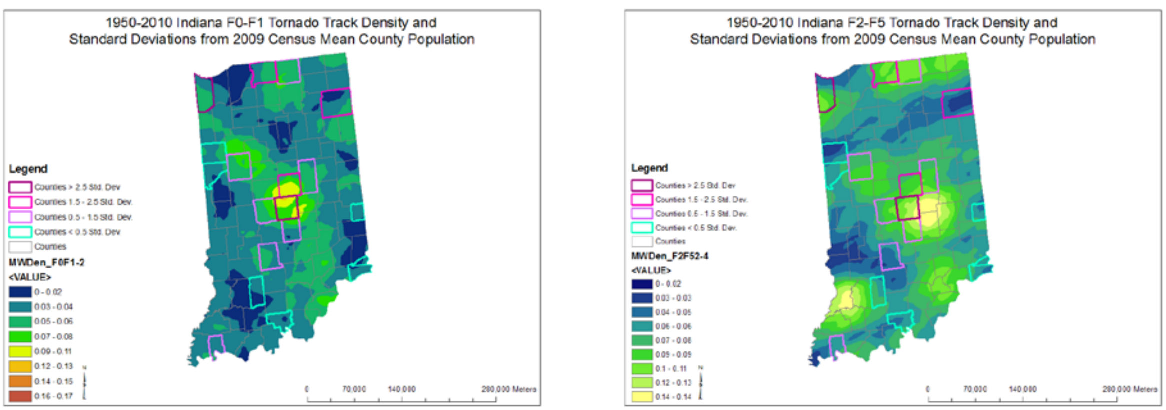
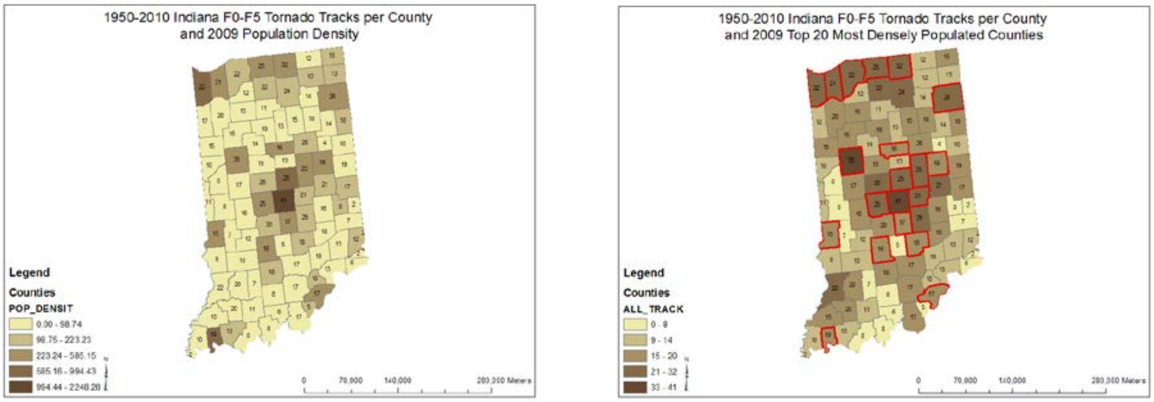


Figure 5: Tornado track density map of strong tornadoes 1974 – 2010 in efforts to remove a possible "strong" tornado bias from methodology used to classify tornado damage and F-scale ranking prior to implementation of the F-scale with the 1974 Super Outbreak. Warm colors on the map indicate regions with higher tornado track density (more reported tornadoes in a given area) and cool colors indicate regions with lower tornado track density (less reported tornadoes in a given area).



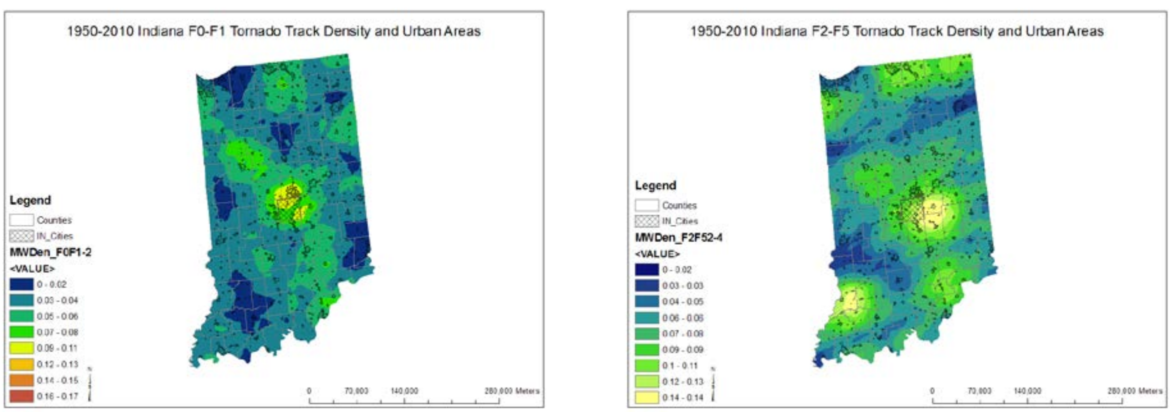
A) B)

Figure 6: A) Tornado track density file for weak tornadoes in Indiana for 1950-2010. Counties with populations greater than +/- 0.5 standard deviations from the mean are highlighted with warm colors (greater than population mean) and cool colors (less than population mean). Warm colors on the map indicate regions with higher tornado track density (more reported tornadoes in a given area) and cool colors indicate regions with lower tornado track density (less reported tornadoes in a given area). B) Same as A) except for strong tornadoes.



A) B)

Figure 7: A) Choropleth map of 2009 population density (persons per square mile) with total number of tornadoes per county 1950-2010 labeled. B) Choropleth map of total tornado tracks per county with top twenty most densely populated counties highlighted in red.



A) B)

Figure 8: A) Same as Figure 5 except with urban regions displayed as hatched areas on the map to note proximity of active tornado regions near urban areas. B) Same as Figure 8 except with urban regions displayed as hatched areas on the map to note proximity of active tornado regions near urban areas.