An Updated Severe Weather Climatology for the National Weather Service Northern Indiana County Warning Area

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I. INTRODUCTION

The National Weather Service (NWS) Northern Indiana office (KIWX) was established in the late 1990s as part of the NWS Modernization and Associated Restructuring (MAR) plan. The KIWX forecast office assumed forecast and warning responsibilities in 1998 for a County Warning Area (CWA) consisting of thirty-seven counties across portions of northern Indiana, northwest Ohio and southwest lower Michigan (Figure 1). In July of 1999, the first comprehensive severe weather climatology for this CWA was published in a NWS Central Region Technical Service Publication (NWS CR-09) by several staff members of the KIWX office. This paper will serve as an update to that publication with a focus on the period 1980-2010.

The original severe weather climatology published in NWS CR-09 (O'Hara et al. 1999) used data compiled from the NWS Storm Prediction Center (SPC) database from 1950 to 1997 as well as official *Storm Data* publications from the National Climatic Data Center (NCDC) from 1959 to 1997. Climatology for severe wind events was developed from data over a period of 43 years, from 1955 to 1997. Climatology for tornado and severe hail was computed over a period of 48 years, from 1950 to 1997. In addition to compiling severe weather statistics and climatology, this previous work also detailed the inherent problems with severe weather reporting, poor spotter networks, and the infancy of storm-data gathering and the impacts these factors had on severe weather statistics.

This updated publication will look at severe weather climatology for the KIWX CWA from 1980 to 2010. This 31-year period will be used to look at trends and statistics in the more modern technological era which has seen the introduction and widespread use of computers, cell phones, digital cameras, smart phones, and social media. In addition to these advances in technology, the NWS has also seen advancements in how it collects, analyzes, surveys, and archives severe weather and damage reports.

A focused effort by the NWS to improve and standardize its official severe weather archive, known as *Storm Data*, has occurred in the last decade and has led to a more consistent database in recent years. Since the modernization of the NWS in the late 1980s and early 1990s, storm data entry has evolved and become more standardized and stringent with improved guidelines. Advances in computer technology and software in the last 30 years have made storm data entry easier while the reports have become more detailed. The dramatic growth in digital recording devices coupled with email, cell phones, the internet and social media have helped lead to the substantial increase in storm reports and documented severe weather by the NWS.

While the NWS has made improvements in formalizing and standardizing storm data entry, it still lacks completeness and in some cases accuracy. Doswell (1988) among many others have documented the potential sources of errors and inconsistencies in severe weather databases, including NWS *Storm Data*. However, the NWS has attempted to address some of these potential errors and inconsistencies through an updated NWS Service Directive on *Storm Data* procedures, an improved and standardized storm data entry program, and the collaborative national upgrade of the Fujita Scale (Fujita 1971) to the Enhanced Fujita Scale (McCarthy et al. 2006) in 2007. Because this paper discusses historic tornado data from both the Fujita and Enhanced Fujita scale periods, we will simply reference all tornadoes using the "F-Scale" nomenclature for consistency.

While the efforts to improve Storm Data have led to a more accurate archive, it is still possible to find errors and inconsistencies. Through the course of collecting and analyzing data for this publication, errors and cases of inconsistent data were found, especially within the tornado databases. Conflicting information was identified among the separate databases from the Storm Prediction Center (SPC), National Climatic Data Center (NCDC), and the National Verification Branch website. This will be discussed further in the data collection section.

The 31-year period from 1980-2010 used in this paper was an attempt to study severe weather in the modern era while reducing and eliminating many irregularities and discrepancies identified in earlier years, specifically with regards to tornado damage and assigned ratings (Brooks et al. 2003; Doswell et al. 2005; Doswell 2007). It is understood that this period may not necessarily be statistically accurate due to sample size limitations and patterns in the data that may be of non-meteorological origin. However, this period should be of sufficient length to identify trends and come up with a useful climatology for the local CWA that forecasters can use as a reference.

This paper will review statistics and trends related to tornadoes, severe thunderstorm wind and hail events, flooding, lightning and rip currents. Rip current data are limited and only available since 2000 but this weather-related phenomenon has been responsible for as many deaths as tornadoes, severe thunderstorm winds, flooding and lightning combined within the KIWX CWA between 2000 and 2010. All of these weather elements will be looked at in detail and favorable times of occurrence by month and time of day will be shown. Comparisons in tornado data will be made to the findings in the previous publication and conjectures about any differences will be offered.

This paper will also discuss and show results from local research which attempts to categorize severe storm types with associated documented tornadoes in the KIWX CWA between 1998 and 2010. This section will break down the storm types responsible for producing each tornado during the 13-year period based on subjective post-analysis of radar data. This will be an attempt to determine the predominant storm type (i.e., supercell, squall line, single cell) responsible for the majority of tornadoes across the KIWX CWA and the relationship between storm type and tornado strength.

II. DATA

Multiple sources of information were used to compile a database of severe weather events for the KIWX CWA. First, the NCDC publishes monthly storm data from each NWS field office in a publication titled *Storm Data*. These monthly documents were used to compile information about tornado, lightning and flood events for the period 1980 to 2010. Second, the NWS SPC has compiled comma separated value (.csv) files for tornado, hail, and damaging wind reports into a Severe Weather Database. These files are SPC’s attempt to digitize the data that have been printed in the *Storm Data* publication. The format of these files is also conducive for use in a Geographic Information System (GIS) program known as ArcGIS, which helps to map the data for evaluation and a better understanding of the geospatial climatology of severe weather events. A third data source was the NCDC storm events database, which also serves as a digital reference of data from *Storm Data* publications. A fourth source of data was the NWS Performance Management website (https://verification.nws.noaa.gov/), which contains information and statistics on NWS warnings and their verification. NWS Weather and Surveillance Radar 1988 Doppler (WSR-88D) data were obtained from NCDC's level II radar archive and utilized to determine storm type associated with tornadoes between 1998 and 2010.

SPC data files were downloaded for the period 1980 to 2010 and were sorted for the KIWX CWA to compile a local database of tornado, hail, and severe thunderstorm wind events. The local database was then used to compute most of the severe weather climatology statistics found in this paper. While comparing tornado events between the multiple databases, numerous errors were found, especially in the tornado database. These errors included instances of duplicate entries of the same tornado, missing tornadoes, incorrect latitude and/or longitude for beginning and ending points, incorrect times for beginning and ending of a tornado event, and tornadoes listed in wrong counties. Every attempt was made to correct the tornado statistics by comparing the multiple databases and eliminating as many obvious errors as possible.

III. KIWX COUNTY WARNING AREA GEOGRAPHY, SOILS AND POPULATION

The KIWX CWA is comprised of thirty-seven counties that include twenty-four counties in northern Indiana, five counties in southwest lower Michigan, and eight counties in northwest Ohio (Figure 1). This also includes approximately 50 miles of coastline along southeast Lake Michigan from near Michigan City, Indiana to St. Joseph, Michigan and the associated near-shore waters which extend out to 5 miles offshore. The NWS Northern Indiana Office provides warning and forecast services for the entire area, including the near-shore waters.

The total land area of the KIWX CWA is approximately 15,875 square miles (2010 U.S. Census Bureau). Allen County in northeast Indiana is the largest county with 657 square miles. Blackford County, Indiana is the smallest with only 165 square miles. Most of the land area is primarily rural farmland with many small towns and several moderate-sized cities. The climatology near Lake Michigan is favorable for commercial fruit orchards while the remaining area is largely agricultural farmland used primarily to grow corn and soybeans.

Soil type across much of northern Indiana and Lower Michigan is sandy loam (Figure 2), which drains well but can dry out very quickly and thus requires large amounts of irrigation and high water usage. This makes portions of far northern Indiana and southern Lower Michigan more susceptible to drought conditions, but also less susceptible to flooding due to good drainage. Soil conditions across much of extreme northeast and east-central Indiana and northwest Ohio are predominately clay soil, which can retain moisture longer, but can also become very hard and dry after prolonged periods of little or no rainfall. This soil type can lead to an increased threat of flooding from heavy rain after long periods of dry weather due to poor drainage and increased run-off.

Elevation changes are minor across the KIWX CWA, ranging from around 580 feet above sea level at Lake Michigan to approximately 1,200 feet above sea level in Hillsdale County, Michigan. An area of slightly higher elevations around 1000 feet ASL bisect the KIWX CWA from northeast to southwest and serves as the divide between the Great Lakes and Mississippi Valley watersheds. Land to the east and west of this continental divide is relatively flat with elevations around 700 feet ASL.

The KIWX CWA has four main river basins: the Maumee, Wabash, St. Joseph and Kankakee basins. Rivers flow in all directions within the KIWX CWA thanks to the proximity of the Great Lakes to the north and east, the Mississippi River to the west and the Ohio River to the south. The St. Joseph basin directs water west and north and empties into Lake Michigan. The Kankakee and Wabash basins direct water west and south. The Kankakee eventually empties into the Mississippi River while the Wabash basin reaches the Ohio River. East of the divide, water is directed into Lake Erie through the Maumee River basin. The NWS Northern Indiana office is located right along the divide separating the Great Lakes and Mississippi watersheds.

According to 2010 statistics from the U.S. Census Bureau, the population of the KIWX CWA is 2,343,404. This is an increase of 183,770 since 1990. Six counties have a population greater than 100,000, which includes Allen, St. Joseph, Elkhart, and Laporte counties in northern Indiana, Berrien County in Michigan, and Allen County in Ohio. Not surprisingly, these counties are home to the larger cities within the CWA including Fort Wayne, South Bend, Elkhart, Goshen, Laporte, Benton Harbor and Lima. The least populated county is Blackford, Indiana with 12,766 people. There are ten counties across the CWA with a population less than 30,000 (Figure 3).

The population density of the KIWX CWA is 147.6 people per square mile. The most densely populated county is St. Joseph County, Indiana at 584.1. Allen County, Indiana is second with 540.8 and Elkhart County, Indiana is third with 425.8. Pulaski County comes in as the least populated county per square mile at just 30.9, with Paulding County, Ohio the second least populated county at 47.1 (Figure 4).

IV. SEVERE WEATHER CLIMATOLOGY INTRODUCTION

Convective severe weather consisting of tornadoes, winds of 58 miles per hour or greater and hail 1 inch in diameter or larger can occur across northern Indiana, southwest Lower Michigan, and northwest Ohio in any month and at any time of day. Severe weather is most prominent in the spring and early summer, but a secondary peak, especially with tornado occurrence, has also been observed in the fall. Deep, moist convection (Doswell 1987, 2001) requires sufficient quantities of moisture, low static stability and a mechanism to lift parcels to their level of free convection (LFC) (Doswell 2001). These parameters come together in sufficient quantities in the spring and summer months in the lower Great Lakes region to produce severe weather. During the cool season (October to March), severe weather tends to be associated with unusually moist and unstable air within deep, highly sheared environments (Smith et al. 2008). These types of environments occur less frequently in the cool season but are associated with large tornado and severe weather outbreaks in the Great Lakes region (Smith et al. 2008). These events are also more likely to produce stronger tornadoes (Dean et al. 2006). The KIWX CWA has seen a secondary peak in tornadoes with a large number of significant tornadoes in the cool season since 1980.

Trained weather spotters observe and report severe weather to local NWS offices to aid in the warning decision process and to help verify warnings. Weather spotters include members of local emergency management, law enforcement, first responders, amateur radio operators and the general public. Local media also aid in the warning decision process by relaying reports of severe weather they receive directly to NWS offices. Severe weather reports are disseminated by NWS offices during and after severe weather events through Local Storm Reports (LSR) and severe weather statements. Reports are also logged and stored internally before being entered into *Storm Data*. Reports entered into *Storm Data* are eventually certified as official and published in a monthly *Storm Data* publication by the NCDC. This publication then becomes the official severe weather record for the United States.

A total of fifty-nine weather-related fatalities were attributed to six different weather elements between 1980 and 2010 in the KIWX CWA. These elements included rip currents, floods, lightning, tornadoes, thunderstorm winds and non-thunderstorm winds. The deaths were considered directly related to the element itself as documented in *Storm Data*. Figure 5 shows the distribution of fatalities among the various elements. Rip currents are the leading cause of death with a total of seventeen recorded in the 11-year period from 2000 to 2010. Detailed statistics on rip currents were lacking prior to 2000, but increasing media coverage and greater awareness of this deadly phenomenon in recent years has led to a more conscious effort to monitor and track the events and any related fatalities. Flooding is the second-leading cause of death in the KIWX CWA with fourteen fatalities occurring over the 31-year period, followed by lightning (13), tornadoes (7), thunderstorm winds (7) and non-thunderstorm winds (1). There have been no direct fatalities documented from hail.

Figure 6 breaks down significant weather occurrences within the KIWX CWA into the six most common event types. Rip currents are not listed because of the difficulties and inaccuracies involved in documenting the frequency of occurrence. Severe thunderstorm winds were responsible for fifty-four percent of all significant weather in the KIWX CWA. This included reports of estimated or measured winds of 58 miles per hour or greater and/or any damage. Severe hail comprised the second highest significant weather phenomena observed with twenty-five percent of the reports. The severe hail category encompasses events of three-quarters of an inch or larger from 1980-2009 and the one inch or larger standard that was implemented in 2010. The combination of severe winds and hail from thunderstorms was responsible for seventy-nine percent of all significant weather. The remaining twenty-one percent of significant weather occurred in the form of floods (8 percent), non-convective winds of fifty-eight miles per hour or greater (6 percent), tornadoes (4 percent) and lightning (2 percent).

The number of severe weather events within the KIWX CWA has increased dramatically since 1980 (Figure 7), similar to trends noted in other research (Brooks et al. 2003; Doswell et al. 2005). Through the 1980s and much of the 1990s, the frequency of events gradually increased.

However, in 1998, a dramatic increase occurred and continued through 2010 with an overall higher annual number of events. The 18-year period from 1980 to 1997 saw an average of 119 events per year while the more recent and shorter 13-year period from 1998 to 2010 averaged 310 events per year. Prior to 1998, the highest number of documented events in a single year was 195 which occurred in 1992. Starting with 1998, only two years have had less than 200 events (2002 and 2009) while six years have seen more than 300 events (1998, 2000, 2001, 2003, 2006, and 2010). Three of these years have had more than 400 events (1998, 2001, and 2003).

The dramatic increase in documented storm events can be attributed to a number of factors, with the most difficult to prove being an actual increase in the amount of severe weather. An increase in population density across the United States and a more diligent approach by NWS offices to seek out damage reports for storm data have been discussed by Brooks et al. (2003) and Doswell et al. (2005) as the most likely reasons for the increase in documented events. While little research has been conducted to verify these conclusions, the authors of this paper tend to agree based on more than 20 years of combined experience in NWS forecast offices and work with storm data. In addition to the broad explanation of increased events given above, this paper offers a few other logical explanations tied to local increases seen in Figure 6, several of which could also be argued for increases seen nationally over the last decade.

The most logical conclusion for the dramatic increase in events in 1998 can be tied to the establishment of the NWS Northern Indiana office in Syracuse, Indiana, which assumed warning and forecast operations on March 17, 1998. The introduction of a new WSR-88D and a staff of trained meteorologists likely contributed to an increase in detection of severe thunderstorms which in turn led to more diligent storm damage surveys and more damage being documented.

The late 1990s and early 2000s also marked the beginning of a new era with a dramatic increase in technology and more widespread use of the internet, digital cameras and cell phones. This allowed for increased documentation of severe weather by trained weather spotters as well as the general public. Prior to instant communications and digital cameras, public reports of severe weather or damage may have been ignored or not reported at all due to a lack of credible documentation and proof. The prolific increase in cell phones also meant more people could call in reports immediately as events were ongoing, especially from rural areas. Before cell phones, there was no easy access to communications in remote or rural areas, witnesses may have either forgotten to make their report or made the assumption that the observed phenomena had already been reported.

The internet has also allowed people to communicate more easily through email and avoid hassles of finding phone numbers or addresses of NWS offices. Simple access to NWS email accounts through internet webpages have allowed for a quick, easy, and convenient method by which to share pictures and severe weather reports for an overall increase in reported events.

V. TORNADOES

a. HISTORY OF TORNADOES IN KIWX CWA

Indiana has been referred to as the eastern extent of “Tornado Alley,” in large part due to a secondary axis of higher tornado frequency that extends into north-central Indiana (Kelley et al. 1978). Brooks et al. (2003) have also identified the geographical area comprising the KIWX CWA as being on the eastern edge of a secondary maximum of mean tornado days per year while Concannon et al. (2000) showed the same area within a secondary maximum for strong and violent tornadoes. The KIWX CWA has experienced many significant, famous, and deadly tornado outbreaks that have helped justify it as part of the poorly defined area known as “Tornado Alley.”

The “Palm Sunday” tornado outbreak of April 11, 1965 was arguably the most famous and devastating tornado outbreak to have impacted what is now the KIWX CWA with a total of ten tornadoes and over one hundred fatalities. While the Fujita Scale for determining tornado strength based on damage (Fujita 1971) had not been developed at the time of the event, later subjective analysis revealed that two of these tornadoes were of F3 strength (158-206 mph on F scale) and an astonishing eight tornadoes were rated as F4 strength (207-260 mph on F scale) (Grazulis 1993). These ten tornadoes were responsible for 128 fatalities across ten counties in the modern-day KIWX CWA. St. Joseph, Elkhart, and Lagrange Counties actually experienced multiple tornadoes on this day. Elkhart County was the hardest hit with three F4 tornadoes, one F3 tornado, and sixty-two fatalities (Grazulis 1993). One of the F4 tornadoes was caught on film and the photograph has become famous among tornado pictures. The rare tornado, consisting of two large twin vortices, can be seen in Figure 8. This picture was taken by Elkhart Truth Newspaper photographer Paul Huffman from just south of Dunlap, Indiana (Elkhart County) looking north along U.S. Highway 33.

Just a short nine years later, the modern day KIWX CWA was hit by another famous tornado outbreak, the “Super Outbreak” of April 3 and 4, 1974. This outbreak was responsible for 148 tornadoes and over 315 fatalities across the central United States in a 24-hour period. A total of sixteen tornadoes occurred in the KIWX CWA, two rated as F3 and two as F4, with eighteen fatalities. One of the F4 tornadoes is well known because it had the longest path length of any tornado during the entire outbreak, 109 miles from White County to Lagrange County Indiana. This tornado is also known for the devastating damage and destruction it created, especially in and around Monticello, Indiana in White County.

While the Palm Sunday and Super Outbreak tornado events are known nationally and are the most memorable, the KIWX CWA has also been a part of several other tornado events which have caused significant damage and fatalities and made national headlines. On March 28, 1920, an outbreak, which some have named the “original” Palm Sunday tornado outbreak, occurred across parts of the Midwest and southern United States with over thirty tornadoes and 171 fatalities (Grazulis 1993). A total of thirty-eight people were killed in the modern era KIWX CWA as two F2 tornadoes, one F3 and three F4 tornadoes moved through the area. The three F4 tornadoes were responsible for all the fatalities. The first F3 moved through Steuben and Branch Counties, killing two people. A second tornado moved through Wells and Allen Counties in Indiana then into Defiance, Paulding, Henry, and Fulton Counties in Ohio killing nineteen people along its path. The third F4 tornado moved through Jay and Adams Counties in Indiana and Van Wert County in northwest Ohio killing seventeen people along that path (Grazulis 1993).

On October 24, 2001, an outbreak of ten tornadoes occurred in the KIWX CWA producing three F2 tornadoes and two F3 tornadoes. This outbreak was responsible for two fatalities. A year later on November 10, 2002, four tornadoes occurred across eastern Indiana into northwest Ohio. This included a large F4 tornado that ripped through the city of Van Wert, Ohio along its 53-mile path. These four tornadoes were responsible for four fatalities and twenty-six injuries. The Van Wert tornado made national news because it obliterated a movie theatre that had been full of people when warnings were issued. Immediate evacuation and sheltering saved the lives of all patrons at the theatre. This was also the last F4-rated tornado to impact the KIWX CWA through 2010.

While there have been many significant F2-F4 tornadoes in the KIWX CWA, there has never been an official F5 rated tornado. However, Grazulis (1993) does list one of the Elkhart County Palm Sunday 1965 tornadoes as an F5 but official NWS records list this as an F4.

b. TORNADO CLIMATOLOGY 1980-2010

Tornadoes have occurred in every county of the KIWX CWA during the period 1980-2010 (Figure 9). Van Wert County, Ohio had the most tornadoes with twenty while Starke and Blackford counties recorded the least with two each. With the exception of 1999 when no tornadoes were recorded in the entire KIWX CWA, there have been at least two tornadoes each year since 1980, with a maximum of thirty-three in 2010 (Figure 10). A total of 265 tornado tracks have been recorded for an average of 8.5 tornadoes per year in the KIWX CWA. This is slightly below the 1950-2010 average of 8.8.

Tornadoes have occurred during all times of the day and in all months of the year in the KIWX CWA during the period of record from 1950 to 2010. However, there are a few differences when looking at tornado data over the most recent period from 1980 to 2010. During this period, there were no tornadoes recorded in the month of December and only one in the month of January. The winter months of December, January and February remain the least active months in terms of tornado frequency, followed by November and September (Figure 11). However, one of only two F4 tornadoes to occur in the KIWX CWA between 1980 and 2010 happened on February 18, 1992 in Van Wert County, Ohio. Ironically, the only other F4 tornado to occur in the KIWX CWA during this period also happened in Van Wert County and also in the cool season on November 10, 2002.

The peak month for tornado frequency was June (71), followed by July (46), May (42) and October (32). A steady increase in tornado frequency can be seen through the spring into the early summer months before a steady decrease occurs from late summer into early fall. However, the month of October stands out with a secondary peak in tornado frequency. This is likely due to the changing seasons which bring sharper thermal boundaries back to the region along with stronger winds aloft. This leads to increased wind shear with height and increased storm-relative helicity (SRH). However, limited moisture and boundary-layer warming keeps convective available potential energy (CAPE) relatively low compared to the higher values seen in the warmer months of spring and summer. Recent studies have suggested that cool-season tornado events (October-March) may be driven more by strong vertical wind shear rather than CAPE (Smith et al. 2006).

Tornado start times were analyzed to determine tornado frequency by hour of the day for the KIWX CWA (Figure 12). The data revealed a steady increase in tornado frequency from late morning through afternoon and into early evening hours, with a peak in activity between 6:00 and 8:00 p.m. EST. A minimum in activity was found between 4:00 and 9:00 a.m. EST. During this period, only one tornado was recorded in each hour over the 31-year period, with the exception of the hour from 5:00 to 6:00 a.m. EST which was the only hour of the day with no recorded tornadoes.

The steady increase in tornadoes through the afternoon hours with a peak in the early evening is no surprise, coinciding with decreasing stability from daytime heating and increasing CAPE. The minimum occurrence was also of little surprise and coincided with the expected period of maximum boundary layer stability and lower CAPE. However, the data did reveal a small secondary peak in tornado frequency between 9:00 and 11:00 a.m. EST when eighteen tornadoes were recorded (nine each hour). These eighteen tornadoes represented about seven percent of all tornadoes to impact the area and eleven of these tornadoes occurred in October; three in June; two in March; and one each in May and July. Further interrogation of the data revealed that the eleven tornadoes in October all came from the same event on October 26, 2010 when a quasi-linear squall line, typical of cold-season tornado outbreaks, moved through the KIWX CWA during the morning and early afternoon hours. This single anomalous event contributed to the secondary peak seen in the data. Without these tornadoes, the secondary peak would likely be inconsequential.

The period of 1980 to 2010 featured three separate and deadly tornado tracks which produced a combined total of seven fatalities. The first deadly tornado occurred on March 27, 1991 in Steuben County, Indiana. This was an F3 tornado that killed one person. The second deadly tornado happened on October 24, 2001 and produced one fatality in LaPorte County, Indiana as an F2 followed by a second fatality in neighboring St. Joseph County, Indiana where the storm grew to an F3. The third and final deadly tornado track occurred on November 10, 2002 when an F4 tornado killed two people in Van Wert County, Ohio then moved into Putnam County, Ohio where it produced F3 damage and killed two more people. It can be seen that six of the seven fatalities in the KIWX CWA between 1980 and 2010 occurred in the months of October and November. All seven fatalities occurred from strong tornadoes rated F2 or higher, which made up only seventeen percent of all tornadoes in the KIWX CWA during this period.

Tornado data for the most recent 31-year period from 1980 to 2010 was compared to the previous 30-year period from 1950 to 1979 to identify any changes in trends and frequency of tornadoes. The number of total tornadoes was relatively similar with 274 recorded in the first 30-year period and 265 recorded during the most recent period. However, there were significant differences when these numbers were broken out based on their Fujita Scale rating (Figure 13). A significant increase in the number of F0 tornadoes was observed over the last 31 years with the number more than doubling from fifty-one to 116. This trend is in line with similar trends cited by Brooks et al. (2003); McCarthy and Schaefer (2004); and Doswell (2007). Only a slight increase in the number of F1 tornadoes was noted. The most dramatic and arguably significant difference was in the frequency of strong (F2 or greater) tornadoes. A substantial decrease in the number of strong tornadoes was found with only forty-five occurring between 1980 and 2010 compared to 110 between 1950 and 1979. The number of F2 and F3 tornadoes was more than half the previous period while the frequency of F4 tornadoes decreased by an astounding eighty-five percent from thirteen tornadoes to just two.

One of the most obvious explanations for the decrease in strong tornadoes can be attributed to the large tornado outbreaks of 1965 and 1974. These two events alone accounted for twenty-seven of the 110 strong tornadoes, or about twenty-five percent, between 1950 and 1979. While there have been significant tornado outbreaks in the KIWX CWA during the most recent period, they have not been on the scale of these past events with respect to tornado strength. More recent tornado outbreaks have spawned large numbers of tornadoes but with a high frequency of F0 and F1 and fewer F2 or stronger tornadoes.

Another explanation can be attributed to tornado ratings prior to the development of the Fujita scale being assigned subjectively after reviews of newspaper articles, photographs and eyewitness testimonies. This has been well documented in the literature as providing a high bias with respect to F-scale ratings (Doswell and Burgess 1988; Brooks et al. 2003; McCarthy and Schaefer 2004; Doswell 2007). These reviews likely did not take into account such factors as structural integrity, quality of construction, or whether damage was a direct result of wind from the tornado itself or possibly from other debris. Brooks et al. (2003) and Doswell (2007) also discuss many undesirable trends, some with non-meteorological origins, which are manifested in the early years of the tornado database. These factors have likely contributed to a unrealistically high number of F2 or greater tornadoes. While the actual reasons behind the differences may never be fully understood, future climatological studies similar to this one may reveal a clearer picture of actual tornado trends.

c. COUNTY TORNADO RATINGS

Tornado intensity will vary along and across its path producing various magnitudes of damage as a result (Doswell and Burgess 1988). The F-scale rating assigned to any single tornado is determined by the maximum observed damage at any point along that path. This can be misleading when attempting to categorize the climatological distribution of tornado ratings for individual counties since tornadoes often move through multiple counties. Additional problems and concerns with tornado ratings and damage paths are discussed in greater detail in Doswell and Burgess (1988) and Verbout et al. (2006).

In an attempt to more correctly assess the F-scale rating for each county based on the damage produced in that county, the tornado tracks listed in the SPC database were separated into individual county tornado events. The NCDC Storm Database and *Storm Data* publications were then used to determine the F-scale rating that was assigned to each county based on the damage and rating listed and not from the maximum intensity assigned to the tornado path. While this methodology still does not account for various magnitudes of damage within a county, it is more representative of maximum tornado strength within each county when compared to the SPC database.

The numbers discussed in this section reflect the total number of tornadoes which impacted each county and their associated damage over the period of 1980 to 2010. These numbers reflect a larger number of tornadoes compared to those derived from the SPC database since a single tornado path covering multiple counties will be broken down into separate events for each county. For example, as previously mentioned in this paper, a total of 265 tornadoes occurred in the KIWX CWA during the period of 1980 to 2010. However, when these tornado paths are separated by county, a total of 303 tornado events are identified.

County tornado events for the period of 1980 to 2010 showed a high percentage of tornadoes in the F0 and F1 range (82%) with a much smaller percentage in the significant category of F2-F5 strength (18%). A total of 303 tornadoes were recorded in the thirty-seven counties within the KIWX CWA with 130 of these being rated as F0 (43%) and 118 rated as F1 (39%). There were a total of fifty-five strong tornadoes (18%), rated F2 or greater, and no tornadoes rated as F5. Of the fifty-five strong tornadoes, forty-one were rated as F2 (13%), twelve were rated as F3 (4%), and only two were rated as F4 (1%) (Figure 14).

The months of May, June, and July were most favorable for F0 and F1 tornadoes (weak) with a significant secondary peak occurring in October (Figure 15). There were fifty-eight weak tornadoes in June with forty-two in both May and July. October recorded thirty-nine weak tornadoes, with many of these occurring during two separate large events on October 24, 2001 and October 26, 2010. These two events produced thirty-two out of the thirty-nine weak October tornadoes (82%) and contributed to the anomalous spike seen during this period.

The frequency of strong tornadoes also peaked in June with sixteen of the fifty-five strong tornadoes (29%) occurring in this early summer month (Figure 16). October had the second largest number of strong tornadoes with ten (18%). These strong October tornadoes occurred primarily during two large events, October 24, 2001 and October 18, 2007. The October 24, 2001 event produced three F2 tornadoes and two F3 tornadoes. The October 18, 2007 event produced two F2 tornadoes and one F3 tornado. The two remaining strong October tornadoes occurred separately, one in Elkhart County on October 16, 1988 (F2) and one in Allen County Indiana on October 8, 1992 (F2).

July represented the third-most significant month for strong tornadoes with a total of nine (16%). The warm season months of April through September accounted for thirty-six strong tornadoes (65%) while the cool season months of October through March accounted for nineteen strong tornadoes (35%). No strong tornadoes were recorded in December or January during this period.

d. TORNADO DAYS

Tornado days can be used to look at tornado data without potential reporting biases such as multiple reports of the same tornado, inflated tornado numbers due to large single day outbreaks, or increasing trends in reported tornadoes over time (Changnon and Schickedanz 1969; Brooks et al. 2003; McCarthy and Schaefer 2004). This study looks at tornado days to understand the frequency and time of year in which tornado events (a day with one or more tornadoes) tend to occur within the KIWX CWA, including the frequency of strong tornado events (a day with one or more F2 or greater tornadoes).

There was a total of 138 tornado days for the period 1980 to 2010 with an average of 4.5 tornado days per year. There were only two years in which the annual number of tornado days equaled or exceeded ten and eight years in which there were two or less tornado days (Figure 17). The number of annual tornado days with strong tornadoes (F2 or greater) can be seen in Figure 18. It is interesting to note that there were only six years with more than a single day of F2 or greater tornadoes. The combined 5-year period from 1993 to 1997 had only one day of strong tornadoes, which occurred on April 26, 1994.

June and July had the most number of tornado days with a total of thirty-three in each month (Figure 19). May was second with twenty-two followed by August with fourteen. Both June and July averaged 1.06 tornado days per month and were the only months with an average of at least one tornado day per month over the period. The standard deviation for tornado days in June was 1.24 while July was 1.21. June had only three years in which the number of tornado days were at least one standard deviation above average; 1980 (4), 1998 (3) and 2010 (5). The year 1980 was just over two standard deviations above average while 2010 was just over three standard deviations above normal. July also had three years with the number of tornado days at least one standard deviation above average: 1987 (3), 1992 (5), and 2003 (4). The year 2003 was just over two standard deviations above average while 1992 was just over three standard deviations above average.

The secondary peak in tornado frequency in October is not as obvious in this data set with only a subtle increase noted over September. However, the secondary fall peak in tornado occurrence does show up when looking at strong tornado days by month (Figure 20). June leads the way again with ten strong tornado days, followed by July with seven. October is third with four strong tornado days. Again, this supports findings of Smith et al. (2006 and 2008) which suggest there are not necessarily more tornado events in the cool season, but events that do occur are part of larger outbreaks with a higher frequency of strong tornadoes.

Forecasters need to be aware of the climatological potential for strong tornadoes in the cool season when forecasting a possible tornado event due to a high-shear, low-CAPE environment. It is essential that this information, which is counter to most people’s ideas of tornado occurrence, be communicated to the media, emergency managers, and the general public for better awareness of strong tornado potential in the cool season.

e. TORNADO OCCURRENCE AND ASSOCIATED STORM TYPE

An important but often overlooked aspect of tornado climatology is the storm type associated with tornadoes. Tornadoes can emanate from different types of parent convection besides the typical supercell thunderstorm and associated mesocyclone. The distribution of tornado-producing storm types (TPST) can vary significantly across the continental United States (CONUS) (Trapp et al. 2005) and an understanding of the local weather forecast office’s (WFO) TPST is imperative to the warning process. Understanding the local TPST climatology can help increase forecaster awareness, leading to increased lead time and probability of detection, two important goals of the National Weather Service.

TPST was developed for the KIWX CWA during the 1998-to-2010 period. The WSR-88D radar was brought online in the fall of 1997 with its full suite of reflectivity and velocity products, a mandatory dataset when determining TPST. Previous research supports at least three different types of tornadic convection: supercells (Browning 1964), quasi-linear convective systems (QLCS) (Wakimoto and Wilson 1989; Trapp and Weisman 2003), and other cells which include: non-supercell tornadoes associated with 500-mb closed lows (Davies and Guyer 2004), landspouts (Caruso and Davies 2005; Bluestein 1985), and tropical cyclone remnants (Spratt et al. 1997; McCaul 1987). The above categories were broken down further into subtypes. The additional categories of low-topped supercells (the typical cool-season counterpart to supercells that form in highly sheared, low CAPE environments; Kennedy 1993), dynamically forced QLCSs (QLCS-DF; squall lines that developed in highly sheared, low-CAPE environments associated with strong low pressure systems and a mid-level speed maxima via processes related to shear instability, typically in the cool-season), and non-dynamically forced QLCSs (QLCS-NDF; squall lines that develop in warm-season environments and are associated with mesoscale convective systems in high CAPE and low to moderate shear environments; Wheatley and Trapp 2008).

WSR-88D velocity and reflectivity data were used to classify the parent storm associated with each tornado. Supercells were classified by features identified in Lemon (1976; the presence of a mesocyclone, weak echo region, hook echo, etc.). Supercells could be embedded in a line of storms or isolated. Low-topped supercells exhibited the same features as supercells, but in a very condensed manner. Low-topped supercells typically have very strong velocity couplets with velocity bin gate-gate circulations well over 90 knots in many instances. However, features such as hook echoes and weak echo regions are typically indiscernible due to the condensed low-topped nature of the convective cells (storm tops are generally less than 30,000 feet, with the majority of cells less than 20,000 feet in the KIWX dataset) and radar beam limitations. A circulation was deemed a mesocyclone if the circulation: 1) persisted for two or more volume scans, 2) extended to the storm relative mid-level, 3) was associated with the convective updraft. QLCS tornadoes are not always associated with a mesocyclone, especially QLCS-NDF tornadoes. QLCS-DF tornadoes are again typically cool-season events in which a squall line develops on the nose of a mid-level speed max. Tornadoes are rain-wrapped and are located at the back of or in the heavy precipitation core, not on the leading edge gust front. Tornadoes were typically of a non-descending nature (Trapp et al. 1999), with many tornadic vortices appearing nearly simultaneously over a several-kilometer depth. A deep-layer circulation is usually present in the QLCS segment on the cyclonic shear side of the jet core, which could be classified as a mesocyclone in many instances. Rear-inflow notching is nearly always present. The strongest QLCS tornadoes (in the KIWX CWA), as well as the longest path lengths, are associated with this type of storm system (up to F3). QLCS-NDF tornadoes are typically warm-season events found in well-developed bow echoes where tornadoes develop on the leading edge of the squall line/outflow boundary (gust front) collocated with meso-vorticies or miso-cyclones (Atkins and Laurent 2009). Velocity data circulations can range from weak to strong and are evident growing from the storm-relative low-levels up to the storm-relative mid-levels (non-descending tornadogenesis; Trapp et al. 1999). The “other” category consisted of storm environments that were typically characterized by weak shear and low CAPE, especially with 500-mb closed lows and hurricane remnants. These environments typically featured conditions where CAPE was located very low in the atmospheric profile, and were ideally co-located in the vertical with available shear, a condition which may act to enhance low-level stretching of preexisting low-level vorticity (Davies 2004). Convective cells in this type of environment typically indicate little to no discernible circulation due to the low-centered nature of the circulation and distance from the radar.

The storm type most commonly associated with tornadoes in the KIWX CWA (1998-2010) were QLCSs, with forty-six percent of all tornadoes (Figure 21). In breaking down QLCSs into the DF and NDF categories, it can be seen that the contribution from each storm type is nearly equal, with QLCS-DF systems having a slight edge at twenty-four percent of all tornadoes (Figure 22). Low-topped supercells were the second largest contributor to tornadoes at thirty-six percent. The smallest contributor to tornadoes was the supercell thunderstorm (classic and high precipitation). When examining tornado intensity by storm type, it is evident that the spectrum of storm types narrows significantly as tornado intensity increases (Figure 23). Low-topped supercells and QLCS-DF were associated with the strongest tornadoes F3+ (six events), nearly all of which occurred in the cool season months and were typically spawned by deep surface low pressure systems. Otherwise, all storm types were associated with F0 or F1 tornadoes. An interesting aspect of the data is that most QLCS-DF tornadoes are F1, unlike all other storm types where the highest incidence was F0 (Figure 23). This may very well be due to the associated strong descending jet core that this type of storm system contains, which may often help to “spin up” slightly stronger tornadoes than other storm types typically do. One final aspect of the data relates to the “other” category. Out of sixteen classified events, fifteen (94%) were F0 while only one (6%) was rated higher at F1. Hence, nearly all tornadoes associated with “other” storm types were very weak tornadoes with most having estimated winds of less than 80 mph, limited damage, and no loss of life.

f. VAN WERT, OHIO TORNADO ANOMALY

When it comes to tornado frequency, Van Wert County, Ohio is an anomaly that stands out in the data. Van Wert County recorded twenty tornadoes between 1980 and 2010, including the only two F4 tornadoes in the CWA during this period. The twenty recorded tornadoes are more than twenty-five percent higher than any other county in the KIWX CWA (Figure 9) and between forty and seventy percent higher than neighboring counties. Even more perplexing is that Van Wert is a rural county with a relatively small population compared to other counties in the KIWX CWA. Van Wert ranks twenty-eighth out of thirty-seven counties with a population of 28,744. The population density is 70.1, which ranks thirty-first out of thirty-seven counties. Typically, higher tornado frequencies have been observed in areas of higher population density (Kellner et al. 2011). However, Van Wert obviously does not fit this pattern as its population and areal size fall below the median for all counties in the KIWX CWA. While tornado frequency is considerably higher, reports of hail, wind and floods do not fit the higher frequency pattern seen in the tornado data.

There is no clear explanation for why Van Wert County has experienced so many tornadoes since 1980. It may be a unique combination of topography and climatology, but more likely, it is a result of a diligent emergency management office. Mr. Rick McCoy has been Director of Emergency Management in Van Wert County since 1990. Mr. McCoy is known for his attention to detail and thorough investigations into nearly all weather-related damage reports his office receives. Mr. McCoy reports to the NWS Northern Indiana office regularly when he is notified of damage and consults with NWS KIWX meteorologists when any damage looks suspect as possibly being from a tornado. Mr. McCoy also has a meteorological background with courses in Broadcast Meteorology/Climatology from Mississippi State University and was also a criminal investigator with the Van Wert Sheriff Department prior to becoming Director (R. McCoy 2011, personal communication). This background in meteorology and criminal investigations coupled with his experience of working with the NWS on numerous damage surveys from strong and violent tornadoes may have given him the experience and skill necessary to identify many smaller F0 and F1 tornadoes that may be overlooked in other counties.

VI. SEVERE THUNDERSTORM WINDS AND HAIL

The KIWX CWA is especially prone to severe thunderstorm wind events. For the 31-year period of 1980 to 2010, there have been 3,846 wind events in the CWA. This corresponds to an average of roughly 124 events per year. Severe thunderstorm winds were reported in every month of the year but occurred most frequently during the late spring and summer months. The peak month for severe wind events was June, which recorded 1,044 events, while July was a close second with 991 events (Figure 24). The peak time of day for severe wind events occurred between 3:00 and 6:00 p.m. EST when daytime heating and conditions necessary for severe thunderstorms were maximized (Figure 25).

The hours between midnight EST and 6:00 a.m. EST generally reflected a decreasing trend in reports through the night which would be expected with loss of diurnal heating and increasing stability. However, two different hours stood out in the overnight time frame with slightly higher numbers. The first hour was from midnight to 1:00 a.m. EST when 124 events were recorded. This reflects an increase of more than forty events compared to the hour prior and after. The second overnight hour with a substantial increase was the 5:00 to 6:00 a.m. EST hour with sixty-one events. This is also an increase of more than forty reports from the prior hour and an increase of over thirty reports from the following hour. These late night and early morning increases can likely be attributed to the occurrence of nocturnal mesoscale convective systems (MCS) over the period.

As expected, the number of severe thunderstorm wind and associated damage reports per year has increased since the late 1990s. This is attributed to an increase in population and improvements in technology and communication discussed previously. There also appears to be a direct correlation between number of reports and the population of each county. More populous counties such as Allen County Indiana, Elkhart County, and St. Joseph County Indiana have more reports than less populous counties such as Blackford, Pulaski, Jay and Fulton (Figure 26).

When there is enough instability and ample moisture present in the atmosphere, hail can form in the updrafts of thunderstorms and grow as big as baseball or softball size. Prior to 2010, the threshold for severe hail was three-quarters (0.75) of an inch in diameter or larger. In January of 2010, the criterion was raised to one inch in diameter or larger. For the purposes of this study, severe hail reports were counted using the three-quarters of inch standard from 1980-2009 and the one-inch standard for 2010.

From 1980 to 2010, there were 1,783 reports of hail in the KIWX CWA. This corresponds to an average of roughly fifty-eight severe hail reports per year over the 31-year period. Severe hail has occurred in every month except for December. The peak season for hail runs roughly from April to July with May being the most frequent month for severe hail (Figure 27). Severe hail is possible at any hour of the day but typically is most frequent in the time period between 2:00 and 6:00 p.m. EST (Figure 28).

Severe hail reports increased dramatically in the late 1990s with population growth and technological advances. As is the case with severe thunderstorm winds, there appears to be a correlation between the number of reports and the population of each county. Allen County, Indiana, the most populous county in the KIWX CWA, had the most reports by far of any county with 132 in the 31-year period. Other more populous counties such as St. Joseph County in Indiana, Elkhart County, and Huntington County also had significantly more reports than some of the less-populated counties (Figure 29).

To compare, the one inch standard was applied to the data from the period of 1980 to 2009. Hail reports smaller than one inch in diameter were left out of these statistics. Only 862 out of the 1,783 severe hail reports met the one inch criterion. This amounts to 921 reports of severe hail with diameters between three-quarters of an inch and one inch, which is roughly 52% of all reports in the 31-year period of 1980 to 2010. There were 318 reports of hail larger than 1.75 inches in diameter which accounts for roughly 18% of all reports. As hail size increased, the reports become rarer. There were only twenty-four reports (1%) larger than 2.75 inches in diameter and eight reports (less than 0.5%) that were larger than 4 inches.

VII. FLOODING

Flooding ranked as the second deadliest weather phenomena in the KIWX CWA between 1980 and 2010 with fourteen fatalities. There were a total of 603 flood events recorded in *Storm Data*. This averaged out to about twenty flood events per year and 0.5 direct fatalities per year.

Topography within the KIWX CWA is relatively flat with only minor elevation changes which generally occur over relatively long distances. This flat terrain is attributed to glaciers from the last Ice Age known as the Wisconsinan Glaciation (O’Hara et al. 1999). Steep slopes and narrow river channels which are ideal for flash flooding do not really exist within the KIWX CWA. While flash flooding does occur annually, it is often induced after prolonged heavy rain events and/or rapid snow melt through rising creeks, streams and rivers that overflow and inundate homes, businesses and infrastructure. Rapid runoff from farm fields into nearby ditches and culverts quickly leads to water flowing over county roads and highways. Channels of swift moving water through steep ravines and large elevation changes, which catch people by surprise, do not occur in this area. Many flash flood injuries and fatalities are a result of people driving through flooded areas and being swept away in their vehicles. Because of this blurred line between typical flash flooding and more generalized areal and river flooding, these events have all been combined into one flooding category for this paper.

The number of documented flood events per county can be seen in Figure 30. Williams County, Ohio leads the CWA by a substantial margin with sixty-eight flood events, while Allen County, Indiana is second with thirty-five events, and White County is third with twenty-eight events. The majority of flood events are attributed to river flooding as the top ten counties for flood events have major rivers running through them. It is interesting to note that sixty-six of the sixty-eight flood events in Williams County occurred in years prior to 1999. The reason for this substantial drop off is not clear but it is possible that when the NWS Northern Indiana office took over *Storm Data* entry in the late 1990s, there was a change in philosophy and criteria for entering flood related events into *Storm Data*. Similar but less dramatic trends can be seen in many other counties with fewer flood events reported after 1998.

VIII. LIGHTNING

Lightning is not defined by the NWS as “severe weather” yet it accounts for a large number of weather-related fatalities annually across the United States. According to NWS *Storm Data*, a total of 193 lightning events were documented which led to seventy injuries and thirteen direct fatalities in the KIWX CWA between 1980 and 2010. A lightning event is defined for this study as any lightning entry in NWS *Storm Data* that indicated damage, injuries, or fatalities from direct lightning strikes. Injuries or fatalities which occurred indirectly from a lightning strike, such as someone being injured or killed from a house fire started by lightning, are not counted as a direct event.

Lightning ranks as the third-leading cause of weather-related fatalities behind rip currents and all flooding events in the KIWX CWA since 1980 (Figure 5). This local ranking aligns well with several studies and statistics which have showed that over a 30-year period, lightning kills more people on average in the United States than tornadoes and high winds and is only exceeded by flooding (Holle and Lopez 1998; Curran et al. 2000; NWS Natural Hazard Statistics). It is likely that the number of direct lightning events, injuries and fatalities was actually higher than documented due to poor reporting and inadequate data tracking in NWS *Storm Data* (Ashley and Gilson 2009).

On average, there were 6.4 events, 2.3 injuries and 0.4 fatalities per year from lightning in the KIWX CWA. Allen County, Indiana recorded the most lightning fatalities (3) over the period while Berrien and St. Joseph County, Michigan along with LaGrange County, Indiana recorded two fatalities each. In terms of population density, Allen County ranks second, Berrien fourth, St. Joseph County, Michigan ninth and Lagrange County, Indiana nineteenth. It is a small surprise to see St. Joseph and Lagrange Counties with the second highest number of lightning-related fatalities given their population density. However, only Lagrange County is below the population median for the CWA, and only by about 600 people. Given the relatively low number of documented lightning fatalities in the CWA along with possible reporting limitations, the small sample size makes it difficult to ascertain any statistically significant trends or logical conclusions as to why these counties had the second highest number of lightning fatalities.

There were four counties which recorded double-digit lightning events in the KIWX CWA, all located in northern Indiana (Figure 31). St. Joseph County led the way with twenty-two events, followed by Kosciusko (15), LaPorte (11) and Elkhart (10). St. Joseph, Elkhart and LaPorte Counties represent the second, third and fifth most populous counties respectively in the CWA while Kosciusko ranks seventh. St. Joseph County also has the highest population density of all counties in the CWA (584.1), thus it makes logical sense that this county would have a high number of reported lightning events. Elkhart County is third in population density (425.8) while LaPorte County ranks sixth (186.4) and Kosciusko County ranks eighth (143.8). While these four counties were accountable for about thirty percent of all lightning events, they only accounted for eight percent of fatalities as only a single lightning fatality was reported in Elkhart County during the period.

It is a little surprising to see Kosciusko County with the second highest number of reported lightning events despite its ranking as the eighth-most densely populated county. The higher number of lighting events can likely be attributed to two factors. First, Kosciusko County is the fifth-largest county in square miles (538) and is home to several hundred recreational lakes. During the height of convective season (May-September), the population of Kosciusko County increases substantially due to the influx of several thousand temporary residents known as “lakers.” This increases the population significantly and likely makes Kosciusko county one of the top-five most-populated counties during the summer. Thousands of these people spend the peak summer months for deadly lightning activity (Ashley and Gilson 2009) outside on the lakes and therefore are more vulnerable to lightning strikes compared to people in other counties. A second less likely but possible explanation is that the NWS Northern Indiana office is located in Kosciusko County. This allows greater and easier access to local news reports of lightning events compared to other counties and therefore storm data entries may be more accurate compared to other counties.

Pulaski County, Indiana was the only county in the KIWX CWA that did not register a lightning event. It is quite likely that at least one event occurred in this county over the period but Pulaski has the lowest population density in the CWA (30.9) and second lowest population (13,402). Pulaski is a rural county with large expanses of agricultural land and it is possible that lighting events in such a sparsely populated county may have not been documented or reported to the NWS via local law enforcement or media.

IX. RIP CURRENTS

In May 2005, the NWS Northern Indiana office began issuing marine forecasts and warnings for the near-shore waters of Lake Michigan from Michigan City, Indiana to St. Joseph, Michigan. This stretch of water is approximately fifty miles long and includes the beaches as well as the waters within five nautical miles of shore. In addition to issuing forecasts and warnings for the waters, the NWS Northern Indiana office also issues rip current advisories for the beach areas when dangerous conditions that may lead to rip current are expected.

Rip currents occur when winds and/or waves cause water to “pile up” along the shoreline. Once waves break along the shore, currents develop that help move the water back out away from shore toward the lake. These currents moving directly away from shore are called rip currents. Recent research suggests that rip currents may exist on most beaches on any given day (NWS Rip Current Webpage). However, when winds and waves become strong enough and oriented properly, the speed of water rushing back toward the lake can increase significantly and become strong enough to carry people away from shore. As the speed of the rip current increases, so does the danger of someone being pulled away from shore, especially weak or non-experienced swimmers. The southeast portion of Lake Michigan is especially vulnerable to rip currents. An offshore sand bar runs parallel to shore and helps trap water near the coast line. This aids in creating more narrow and channeled currents along the popular beaches. The combination of these conditions and very popular summertime beaches leads to an increased frequency of rip currents, life-saving rescues, and unfortunate fatalities.

Since rip currents are a deadly water phenomenon created primarily by weather factors, the NWS has taken responsibility for forecasting these deadly conditions and attempting to warn the public of their existence. The NWS Northern Indiana office began keeping track of fatalities in which rip currents were the suspected cause in the year 2000. This has proven to be a very subjective process when trying to determine if rip currents were the reason behind a drowning or if other factors such as poor swimming abilities, alcohol, narcotics, etc. were responsible. In most cases, final determination has been made by local officials and first responders who observed the rip currents or through eyewitness accounts.

Drowning is usually the primary cause of death from rip currents as people are swept away from shore by the current, panic, become quickly fatigued by attempting to swim directly back to shore within the current, and then drown. Many rip current-related deaths have been attributed to weak swimmers or people who were not educated on how to escape a rip current. Anecdotal evidence suggests most deaths are young males (under 30) or children, many of whom are not considered “locals” but are out-of-town visitors to the beaches. It has been suggested that “locals” may be more familiar with not only the conditions and dangers of rip currents, but also the proper methods by which to escape if caught in one.

Rip currents have been responsible for seventeen fatalities between 2000 and 2010 along the 50-mile stretch of Lake Michigan. During this same 11-year period, there have been seventeen fatalities within the entire KIWX CWA from tornadoes, winds, hail, lightning and floods combined. The worst rip current tragedy occurred on July 6, 2003 when seven people died. These deaths occurred in the afternoon hours following a line of severe thunderstorms which had moved through earlier in the day. It is believed that a small seiche occurred on Lake Michigan in the wake of the thunderstorms in addition to the increased northwest winds which developed. These factors led to an increase in wave heights and an increased presence of rip currents.

Tracking fatalities and water rescues associated with rip currents alone is very difficult, in part due to a lack of organized reporting and database tracking. The KIWX staff has tried to remain diligent in maintaining a database of rip current-related fatalities in hopes of improving future forecasts of these events and educating the public on their dangers. It is obvious from this small database that rip currents are deadly and arguably as hazardous as any other severe weather phenomenon. This is likely due to the fact that beaches become heavily populated during the summer months and rip currents can often occur on sunny, pleasant days in the wake of strong cold fronts when strong post-frontal winds develop. It so happens these are also optimal days for high beach activity with people enjoying sunshine and comfortable temperatures. This puts more people at risk in a relatively concentrated area.

X. SUMMARY

Significant weather events in the KIWX CWA have been widespread but also shown substantial increases since 1980 with the most dramatic increases occurring after 1997. Each county in the KIWX CWA has experienced tornadoes (Figure 32), severe thunderstorm wind events (Figure 33), severe thunderstorm hail events of at least three-quarter inch diameter (Figure 34), and hail events at least 1 inch in diameter (Figure 35).

Severe thunderstorm winds and associated damage comprised fifty-four percent of all recorded events while severe-size hail made up twenty-five percent of the reports. Flooding was responsible for eight percent of the events followed by non-convective high wind events (6%), tornadoes (4%) and lightning (2%). All severe weather-related events have shown an increase over the period 1980-2010 with a dramatic increase noted in 1998 which corresponded to the opening of the NWS Northern Indiana Office and likely a more diligent approach to verifying severe weather warnings and investigating damage reports. It is also surmised that a prolific increase in cell phones and digital cameras along with widespread use of the internet have allowed more people to easily document and report severe weather events as they occur.

Rip currents have been responsible for the most fatalities in the KIWX CWA during the period with seventeen recorded deaths. However, statistical tracking of rip current fatalities only began in 2000 so it is assumed with reasonable certainty that the actual number of deaths is much larger for the entire period of record from 1980 to 2010. Flooding was found to be the second-leading cause of death (14) followed by lightning (13), tornadoes (7), severe thunderstorm winds (7), and non-thunderstorm winds (1). The seven tornado-related fatalities occurred from three strong tornadoes (F2 and higher). These fatalities also occurred during the cool season months (October-March) with one in March, two in October, and four in November. The F2 and greater strength tornadoes made up only seventeen percent of all tornadoes in the KIWX CWA during this period yet were responsible for all fatalities.

Annual distribution of tornadoes and severe thunderstorm wind events both showed a maximum occurrence in June while severe hail events peaked in May. Severe thunderstorm winds and hail displayed a rather smooth annual distribution while the tornado distribution showed a distinct secondary peak in October. The majority of these October tornadoes were a result of just two large tornado events. The hourly frequency of these events favored the mid-to-late-afternoon hours. Severe thunderstorm wind and hail events peaked between the hours of 3:00 and 6:00 p.m. EST while tornado events peaked a little later between 6:00 and 8:00 p.m. EST. All events showed a minimum during the early morning hours between 2:00 and 5:00 a.m. EST.

The SPC tornado database was used to determine trends in tornado strength categories for the current 31-year period compared to trends in the previous 30-year period from 1950-1979. Tornadoes in the F0 category showed a substantial increase by more than doubling from fifty-one to 116. The number of F1 tornadoes increased slightly from ninety-two to 104. Strong tornadoes (F2-F4) showed substantial decreases compared to the earlier period. The number of F2 and F3 tornadoes was more than halved with F2-rated tornadoes decreasing from seventy-six to thirty-three and F3 category tornadoes decreasing from twenty-one to ten. The number of F4 category tornadoes had the largest decrease going from thirteen to just two. There were officially no F5-rated tornadoes during either period though Grazulis (1993) classified one tornado from the April 1965 outbreak in Elkhart County as being F5 (the NWS officially lists this tornado as an F4). Overall, the number of total tornadoes in the SPC database decreased slightly from 274 during the 1950-to-1979 period to 265 in the 1980-to-2010 period.

Tornado paths listed in the SPC tornado database were further broken down into individual county tornado events. This allowed for a better determination of actual tornado intensity in each county based on the damage produced in that county rather than on the maximum intensity assigned to a tornado path. These data still showed a maximum in June for tornado occurrence and also showed a secondary peak in October.

Tornado days were computed in an attempt to eliminate skewed data from climatological trends and single events which produce large numbers of tornadoes. A total of one hundred thirty-eight tornado days occurred during the period 1980-2010 with the peak number of tornado days occurring in June and July with thirty-three days each. Therefore the average number of tornado days in June and July was about one (1.06). The secondary peak of tornadoes in October was nearly eliminated when looking at tornado days with only a subtle increase noted over September. The secondary peak does remain in place when looking at days producing strong tornadoes. This further supports the idea that the frequency of fall tornado events is not necessarily greater but when they occur they tend to produce large numbers of tornadoes in addition to strong tornadoes.

A unique aspect of this severe weather climatology paper investigated the storm types associated with tornadoes which occurred from 1998 to 2010. This period correlates with the beginning of the KIWX WSR-88D and its associated radar products. This allowed for consistent research of radar data with documented tornadoes over the entire period. It was found that forty-six percent of tornadoes in the study area occurred from QLCS storm types while thirty-six percent originated from low-topped supercell thunderstorms. Supercell thunderstorms (classic and high precipitation) were responsible for the fewest number of tornadoes. QLCS events were investigated further to find that nearly twenty-four percent of all tornadoes were from dynamically forced QLCS systems while twenty-two percent were from non-dynamically forced systems. This research also looked at tornado intensity by storm type and found that the spectrum of storm types narrows significantly as tornado intensity increases. Low-topped supercells and QLCS-DF storm types were associated with the strongest tornadoes (EF3 and greater) which nearly all occurred in the cool season months.

Understanding the severe weather climatology for a geographical area such as the NWS Northern Indiana CWA is important for local meteorologists. Data analyzed in this paper will serve as a reference for spatial and temporal severe weather trends as a means of general situational awareness before severe weather begins. The climatological record can give forecasters an idea of what type of severe weather is favored, when to expect it, and impacts it may bring. This might include anticipating significant tornadoes in the cool season when tornado events are forecast. This information can also serve as an important reminder that severe weather can occur during times when least expected. Finally, the climatological data presented in this paper can serve as an important teaching aid in outreach and awareness training for emergency managers, first responders, weather spotters and the general public. Results from this study can be used specifically to teach the importance of being prepared and having an action plan for severe weather during all hours of the day and at all times of the year.

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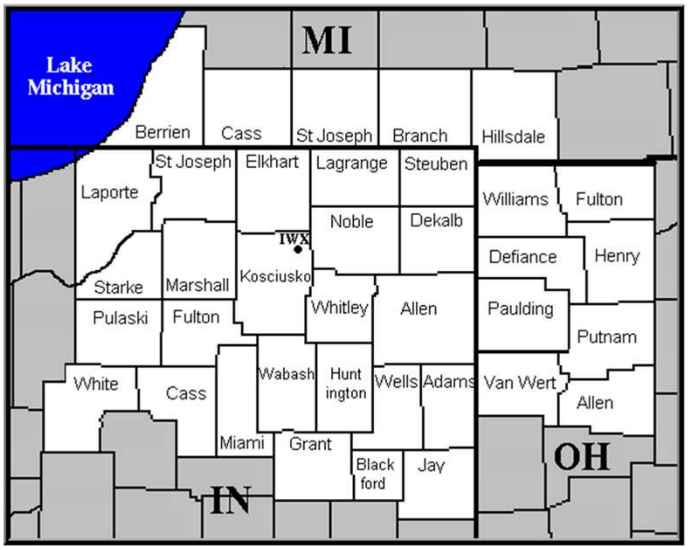


Figure 1. NWS Northern Indiana County Warning Area.

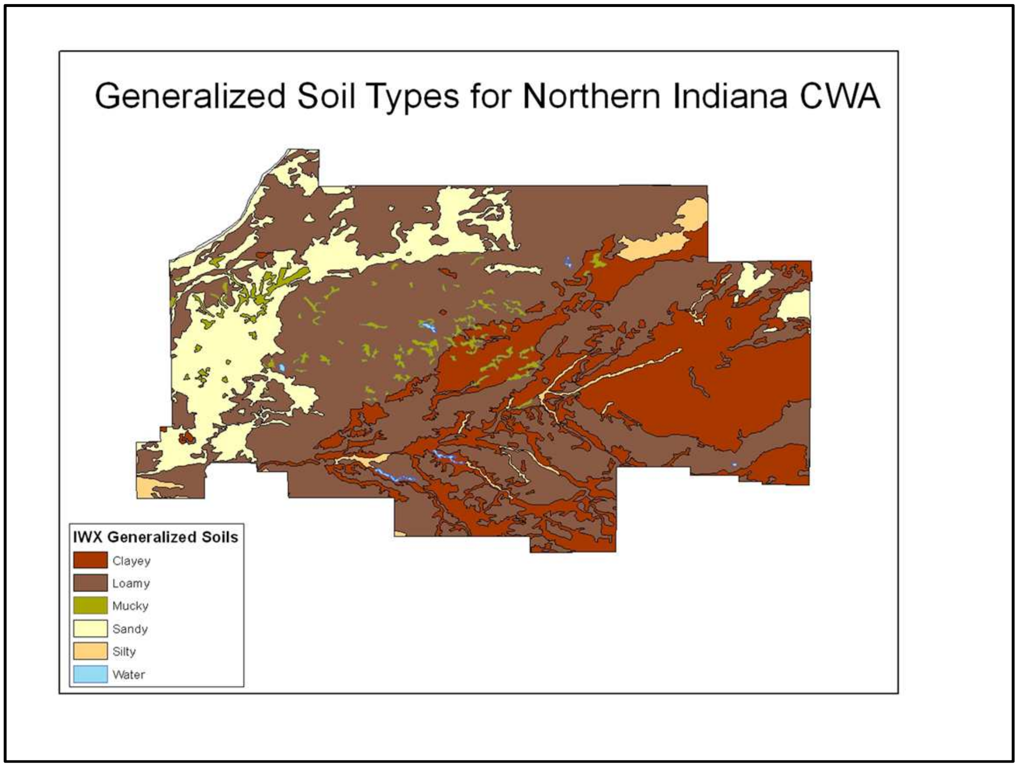


Figure 2. Generalized soil types for KIWX CWA.

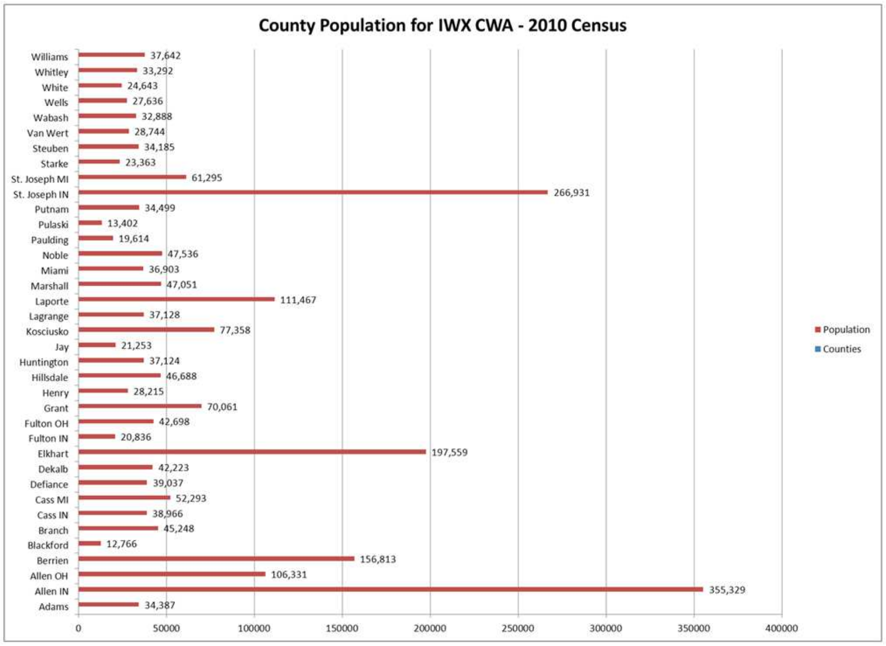


Figure 3. KIWX CWA population by county.

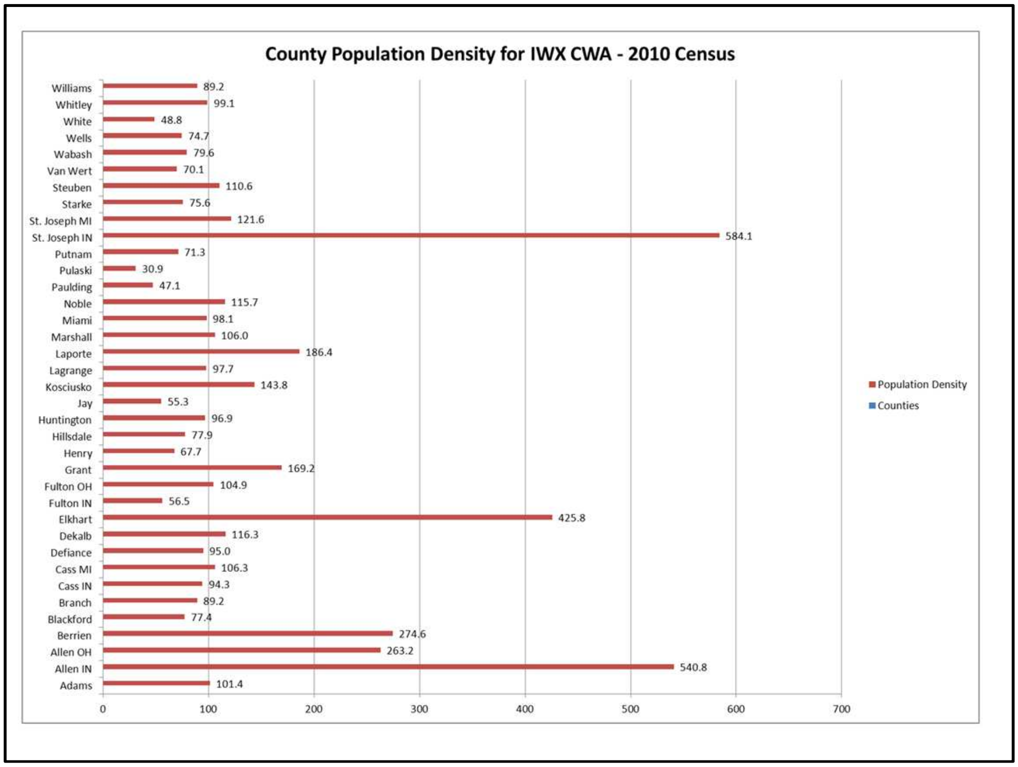


Figure 4. KIWX CWA population density by county.

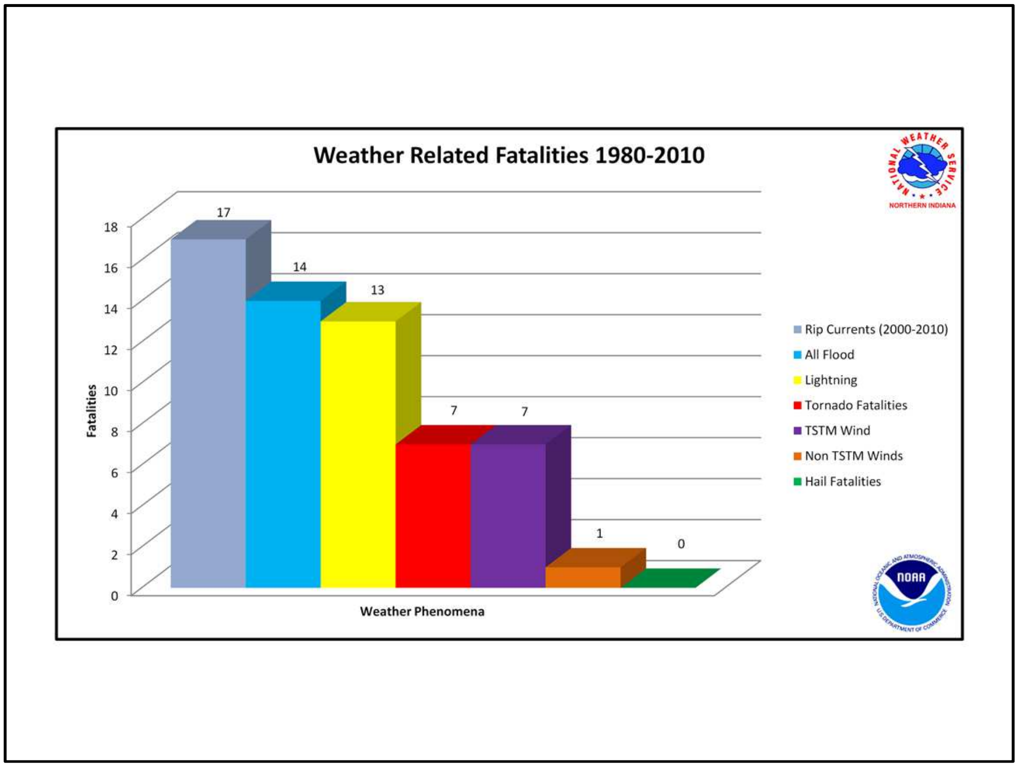


Figure 5. Weather-related fatalities in the KIWX CWA 1980-2010.

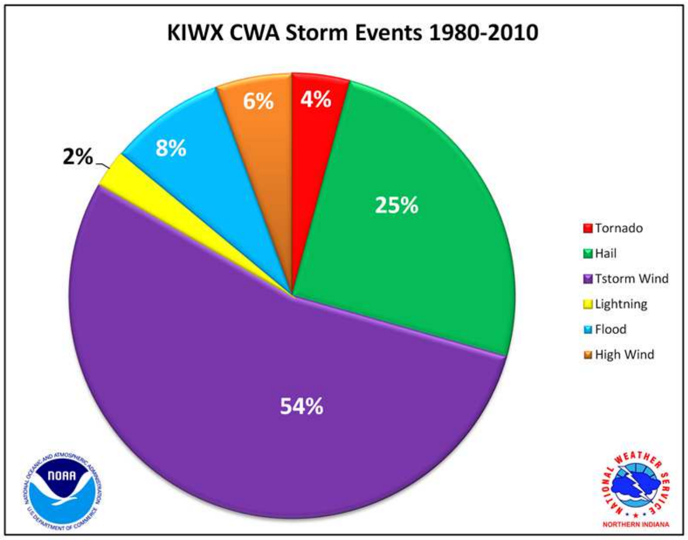


Figure 6. Breakdown of KIWX CWA storm events by category from 1980 to 2010.

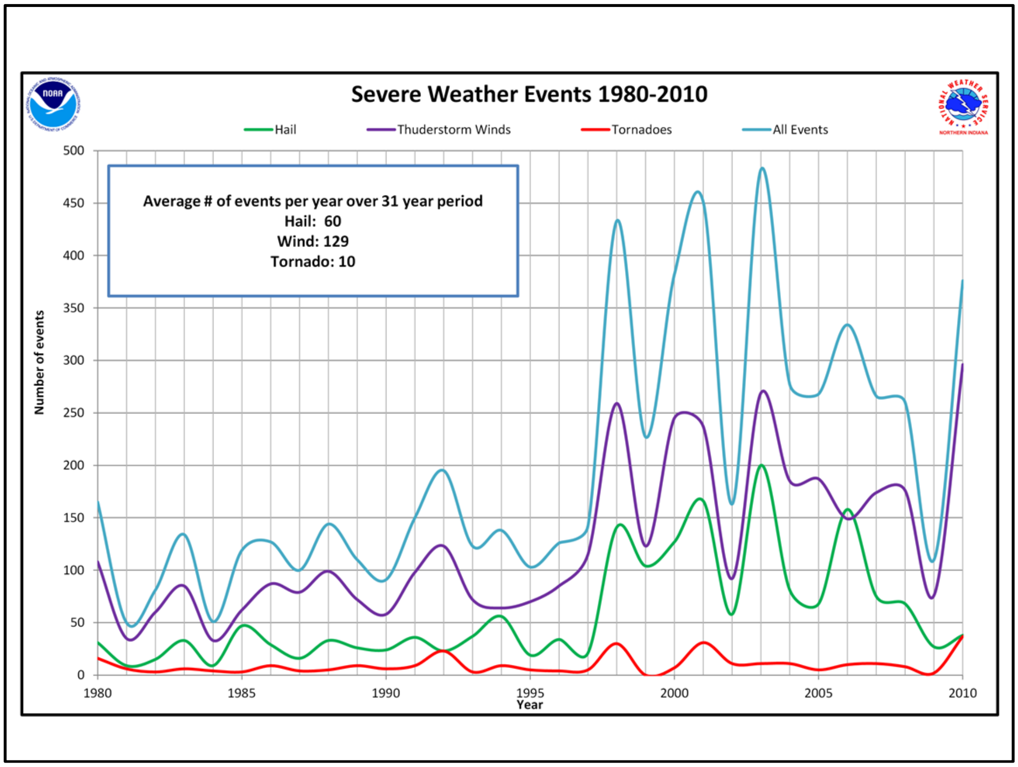
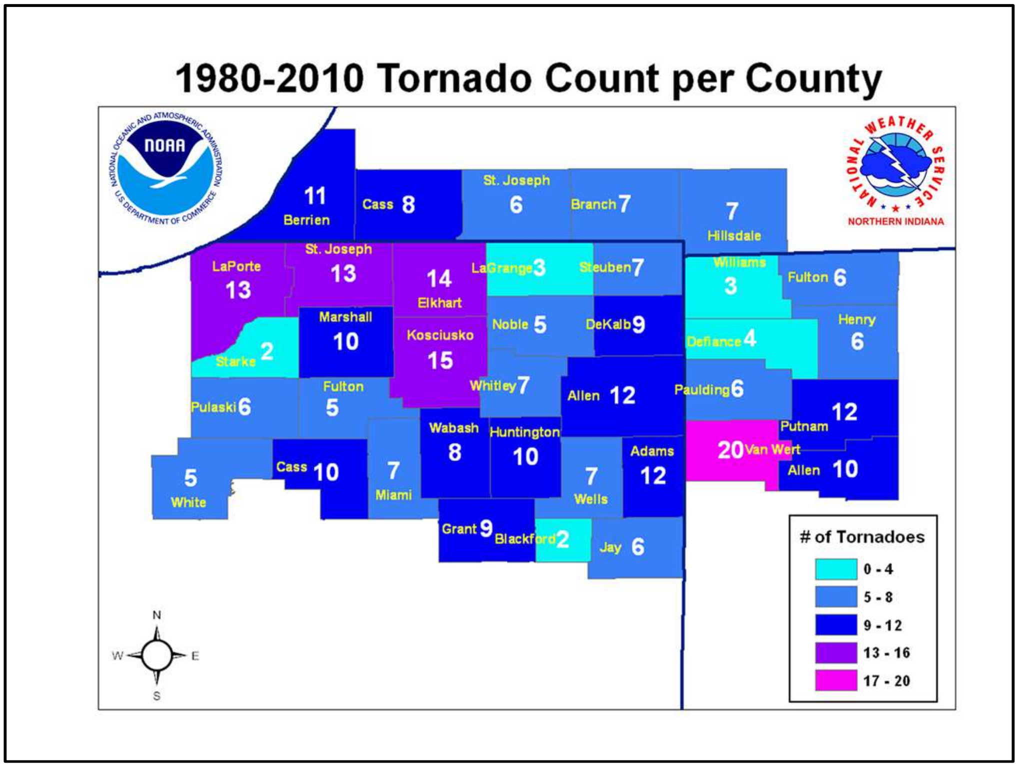


Figure 7. Severe weather events by year for KIWX CWA.

Figure 8. Photograph of “Twin Tornadoes” near Dunlap, Indiana. This picture was taken by Mr. Paul Huffman of the *Elkhart Truth* during the 1965 Palm Sunday Tornado Outbreak.



1980-2010 Tornado Count per County

Figure 9. Tornadoes per county 1980-2010.

Tornado frequency by year 1980-2010 tracks

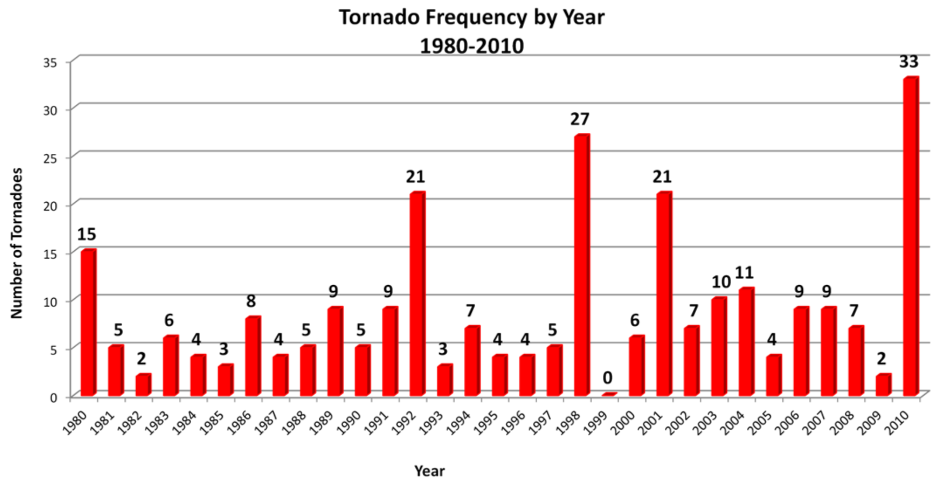


Figure 10. Tornado frequency by year 1980-2010.

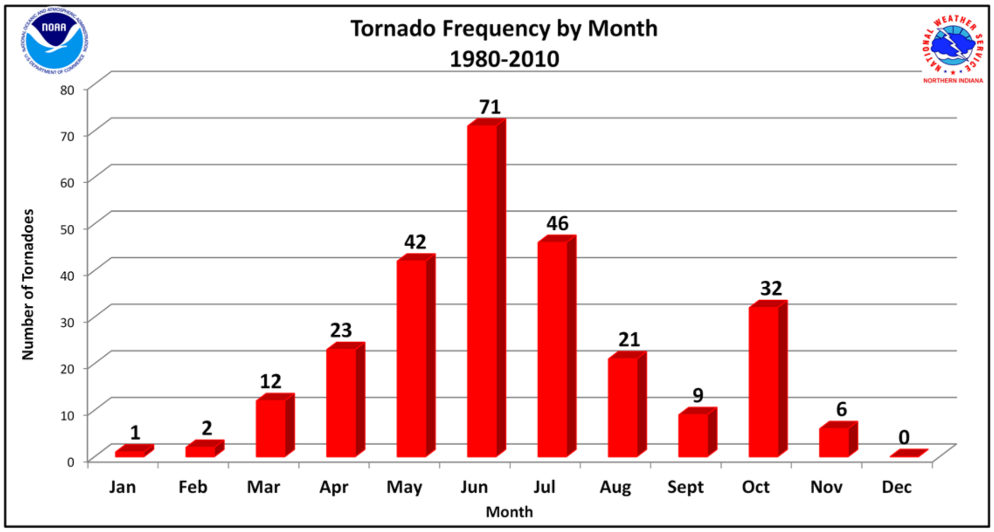


Figure 11. Frequency of tornado events by month 1980-2010.

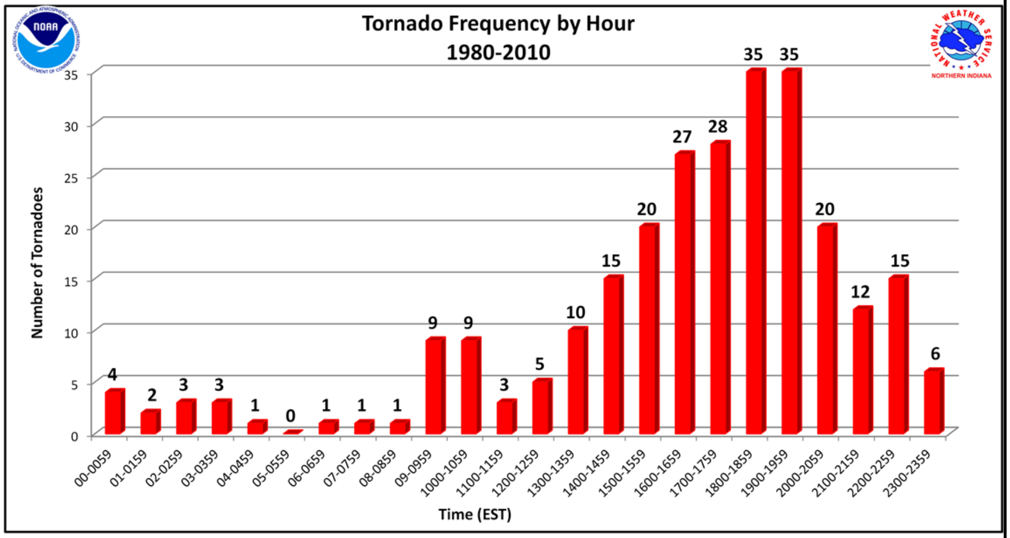


Figure 12. Frequency of tornado events by hour of day.

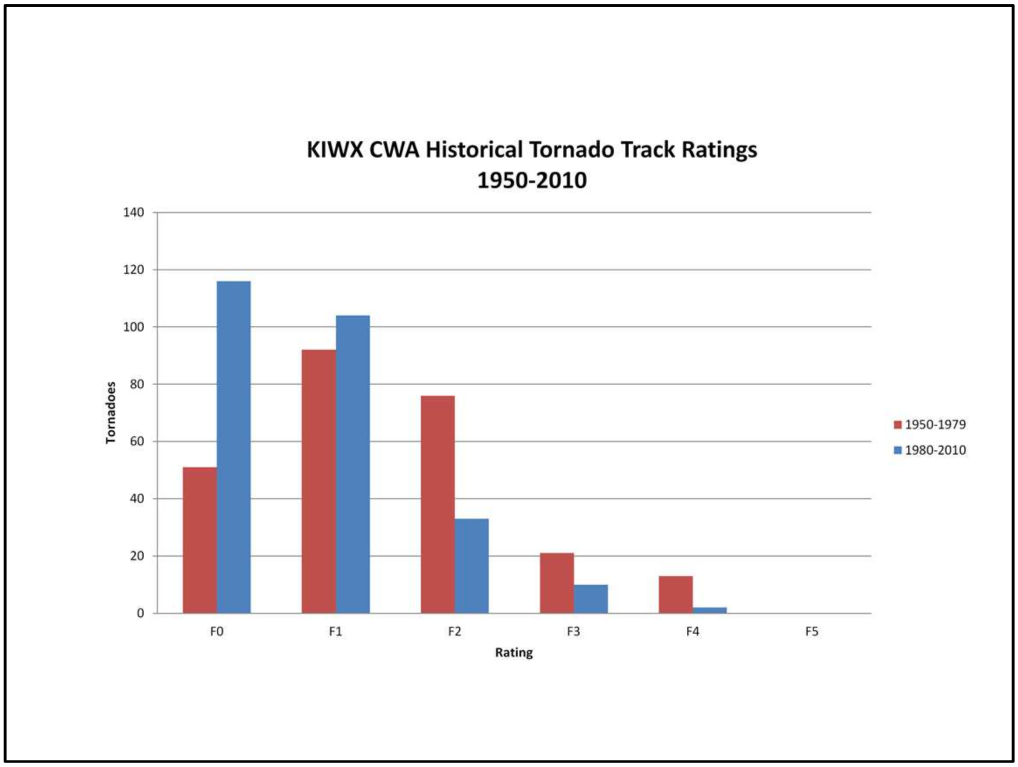


Figure 13. Comparison of tornado F-scale ratings for periods 1950-1979 and 1980-2010.

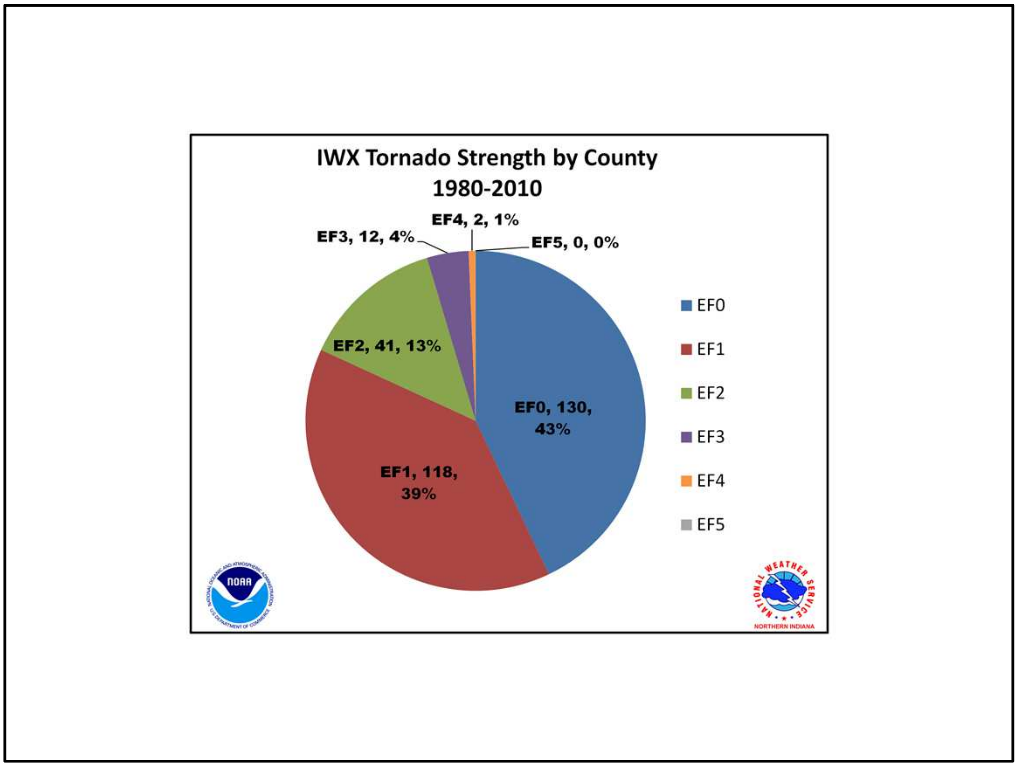


Figure 14. Breakdown of tornado strength categories based on tornado rating by county.

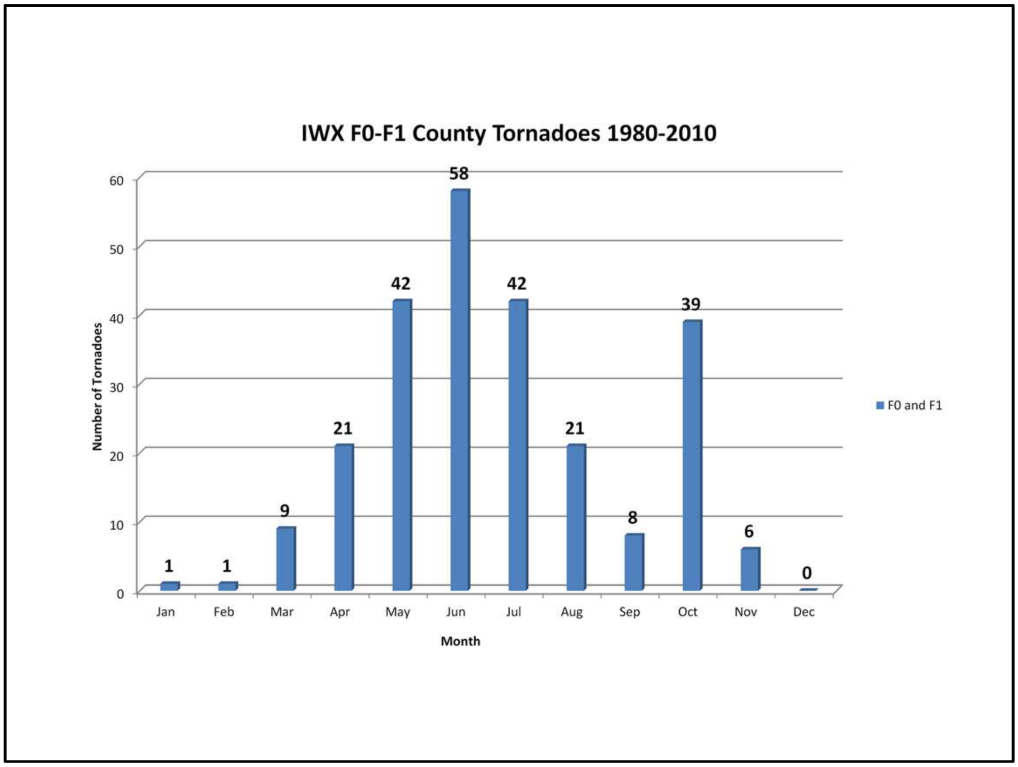


Figure 15. County-based F0 and F1 strength tornado distribution by month.

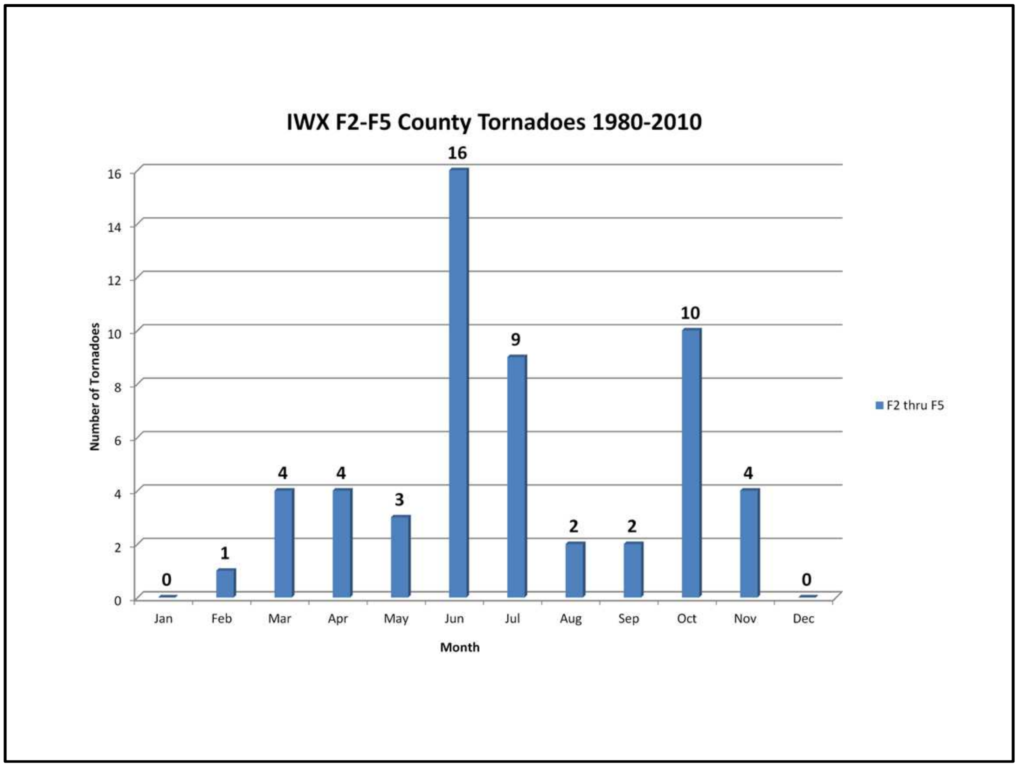


Figure 16. County-based F2 to F5 strength tornado distribution by month.

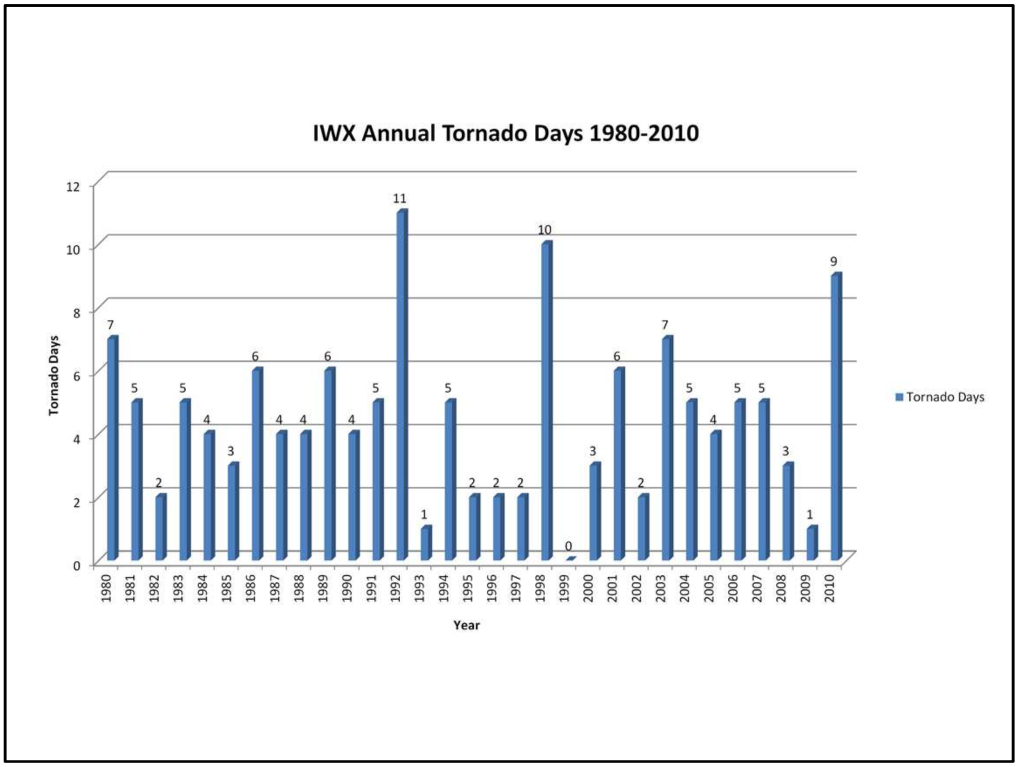


Figure 17. Annual number of tornado days in the KIWX CWA.

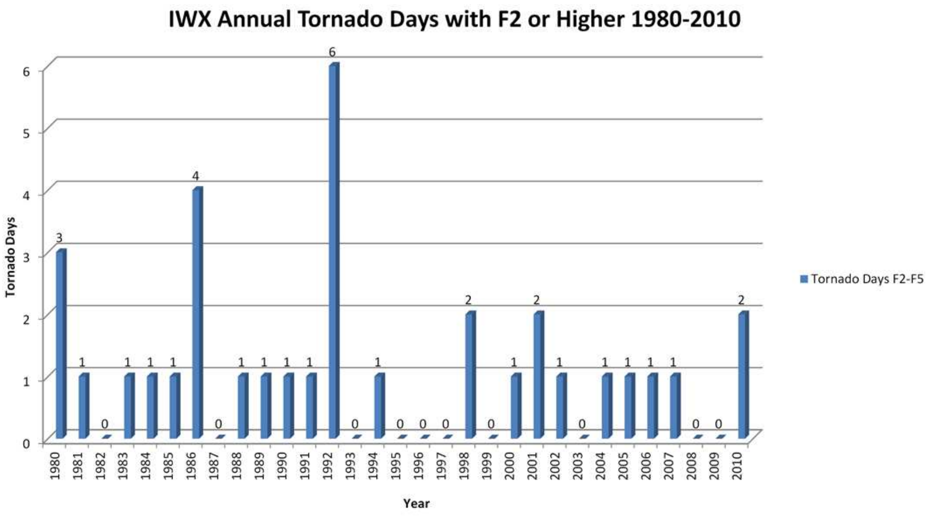


Figure 18. Annual number of strong tornado days in the KIWX CWA.

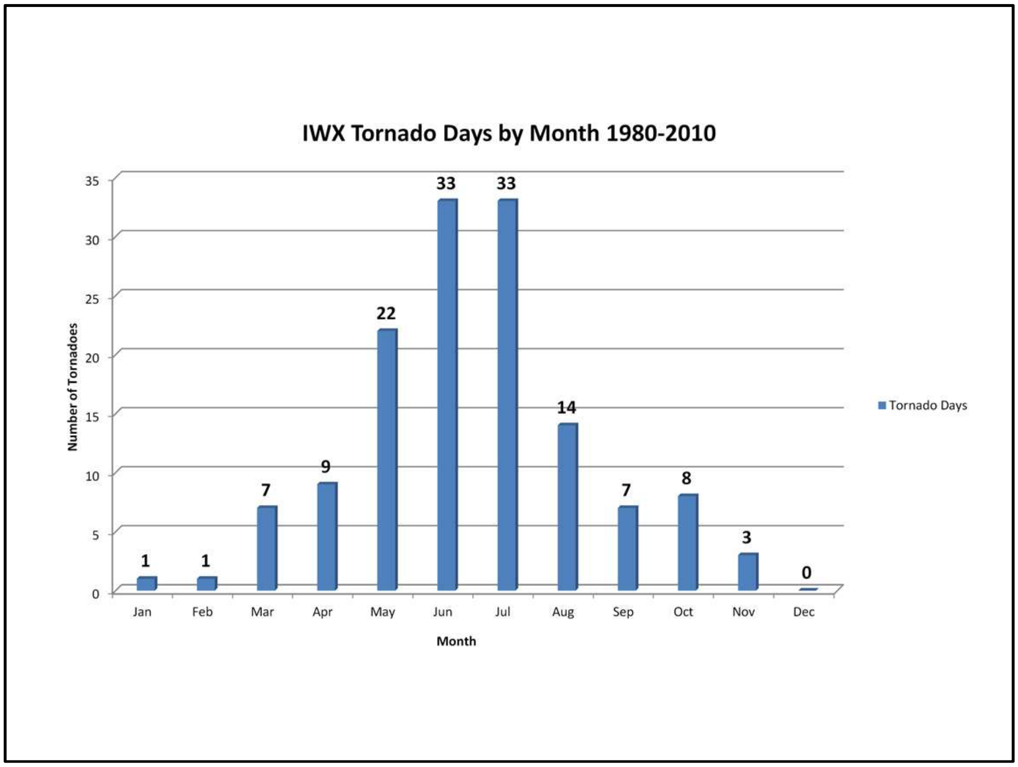


Figure 19. Number of tornado days per month in the KIWX CWA.

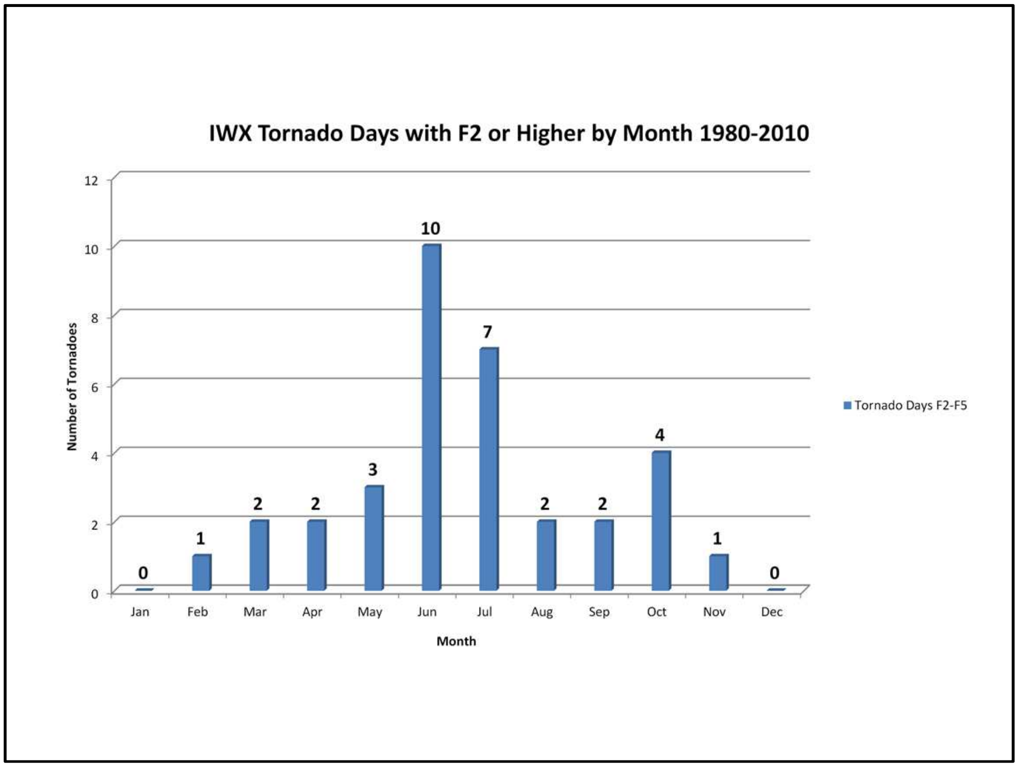


Figure 20. Number of strong tornado days per month in the KIWX CWA.

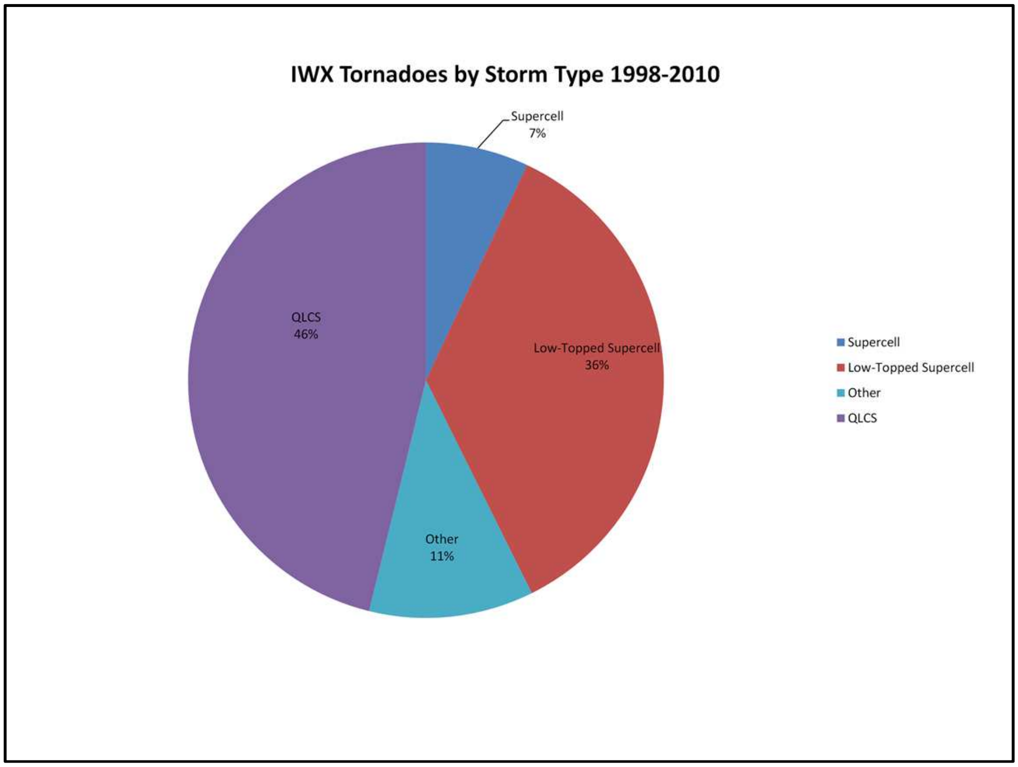


Figure 21. Tornadoes in the KIWX forecast area broken down by storm type from 1998-2010.

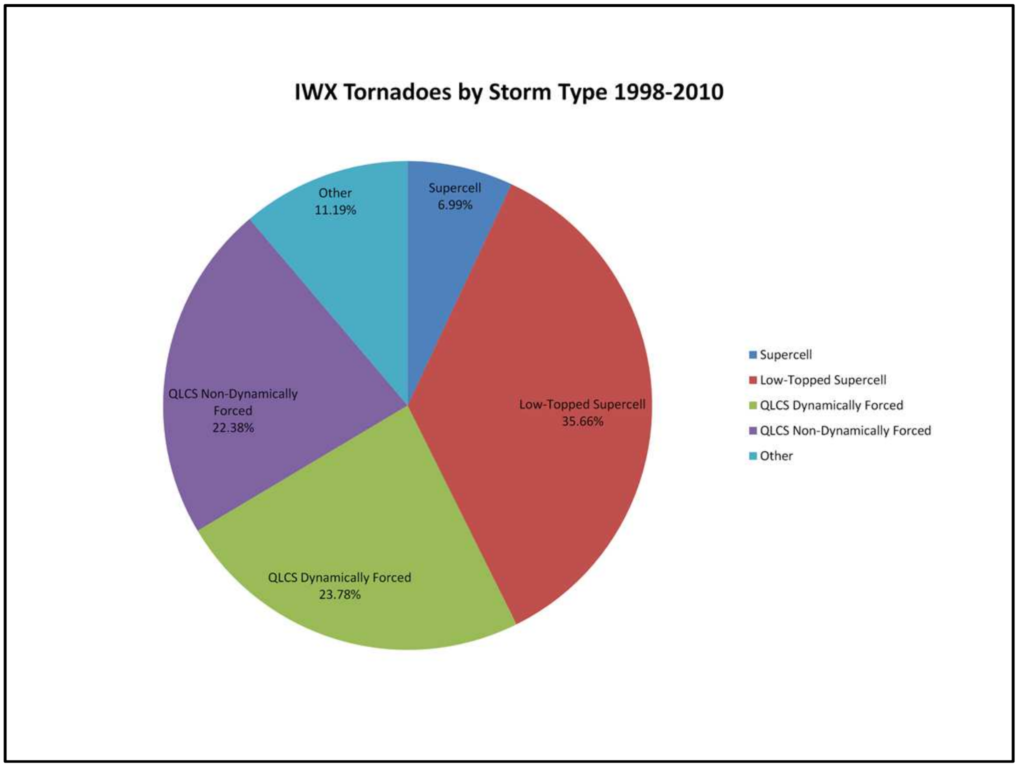


Figure 22. Same as Figure 21, but with QLCS tornadoes separated into DF and NDF categories.

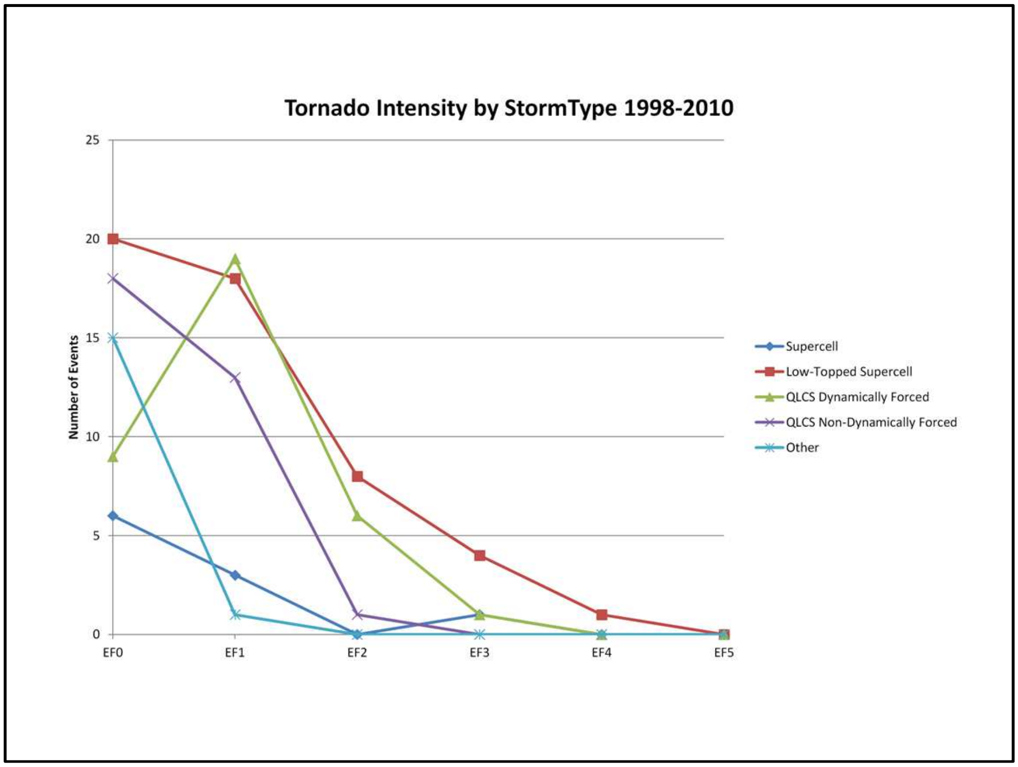


Figure 23. Number of tornado events by storm type broken down by EF scale rating for the KIWX forecast area (1998-2010).

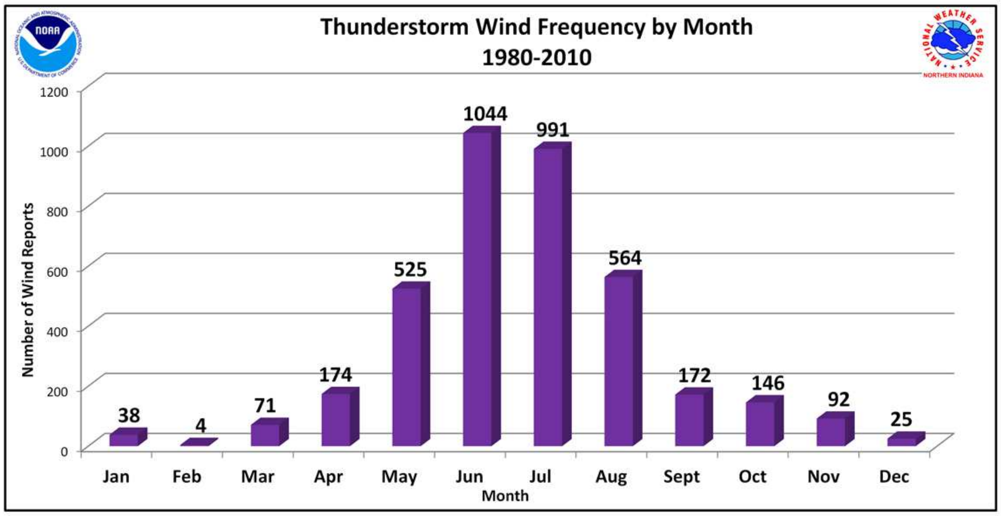


Figure 24. Frequency of severe thunderstorm wind events by month.

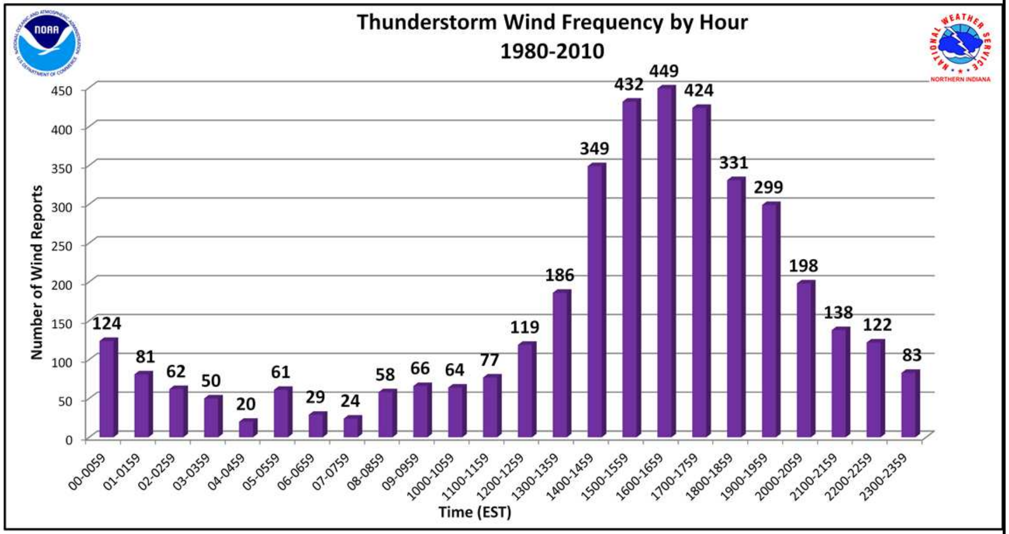


Figure 25. Severe thunderstorm wind frequency by hour.

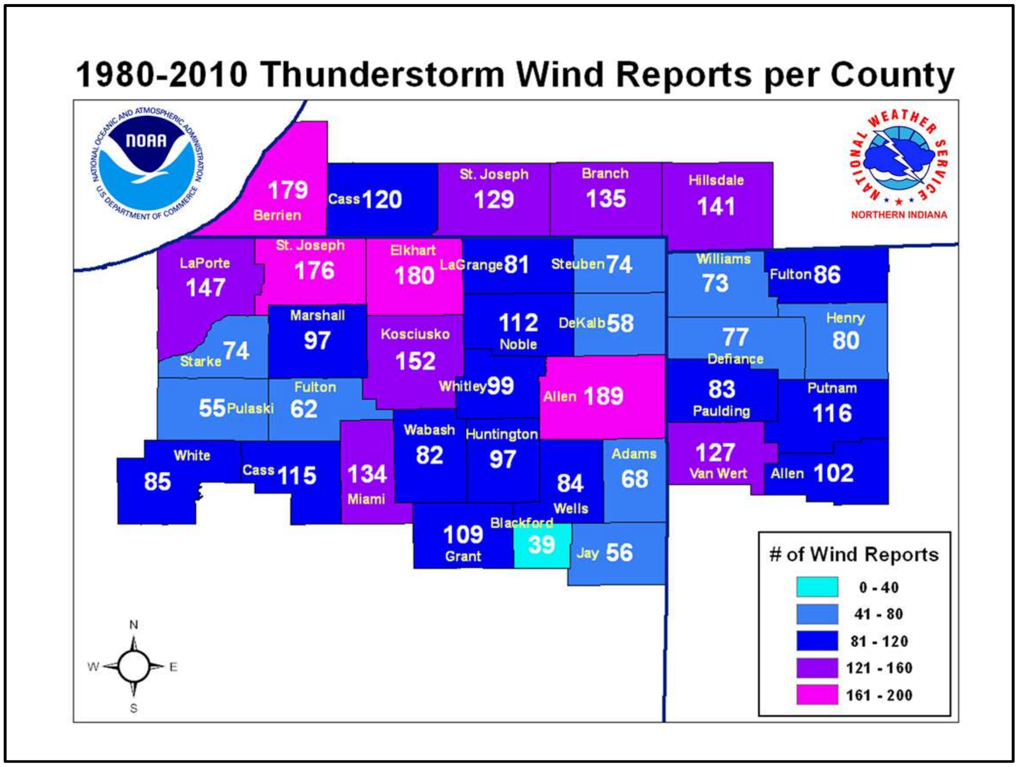


Figure 26. Number of severe thunderstorm wind reports per county.

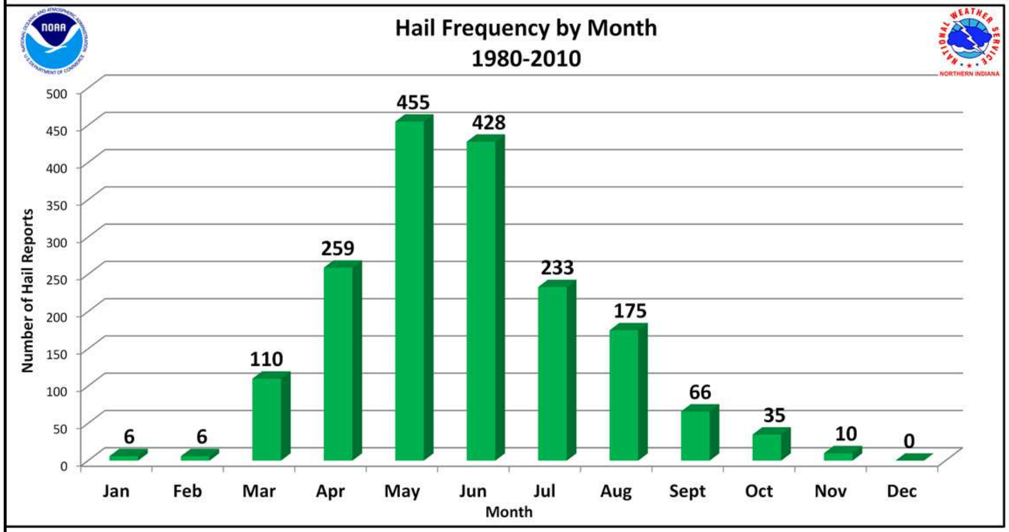


Figure 27. Frequency of severe hail events by month.

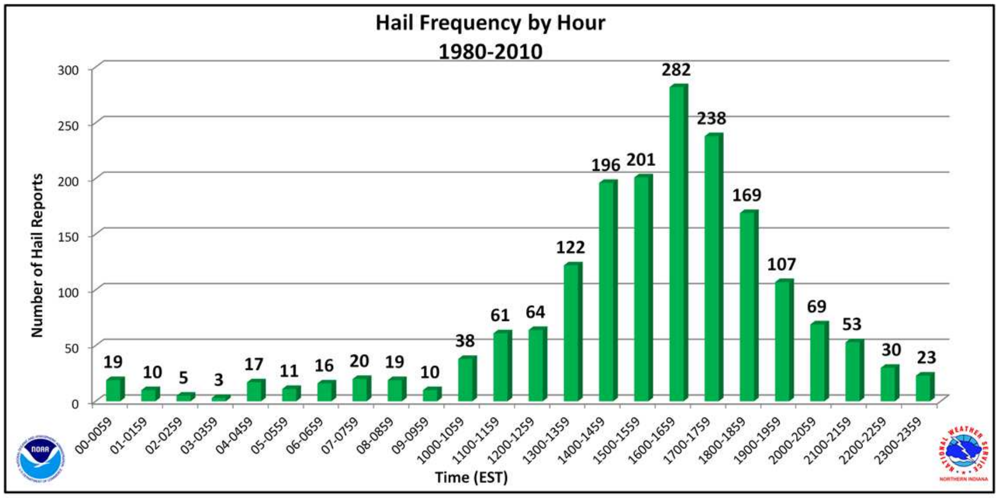
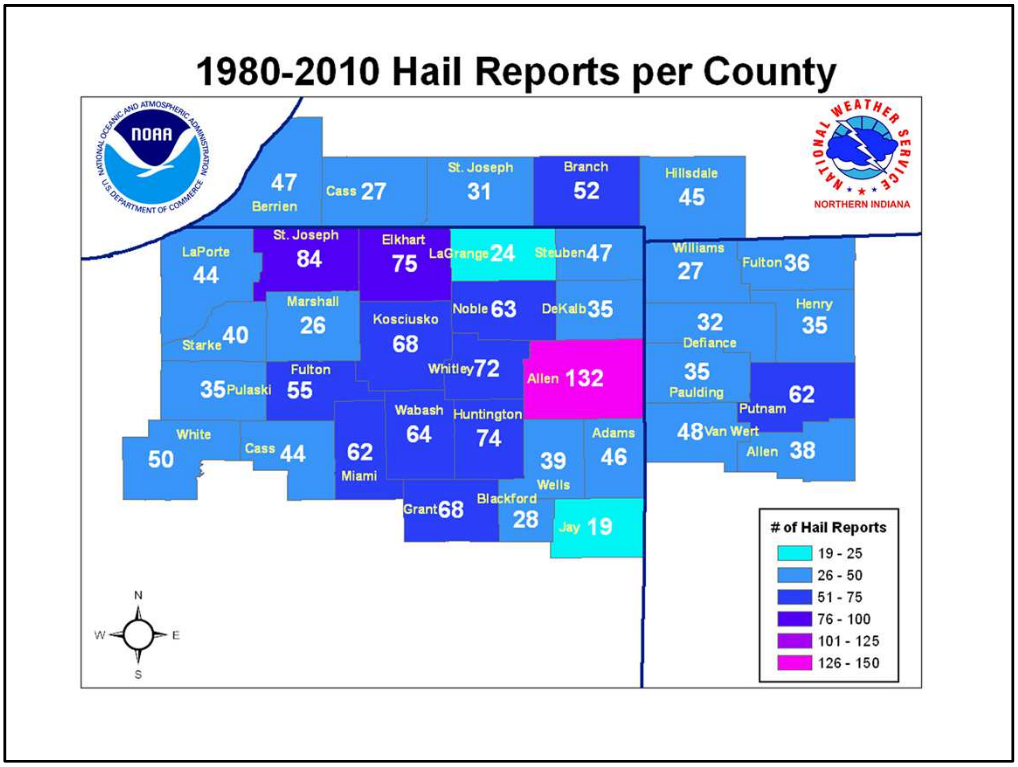


Figure 28. Severe hail frequency by hour.



1980-2010 Hail Reports per County

Figure 29. Number of severe hail reports per county.

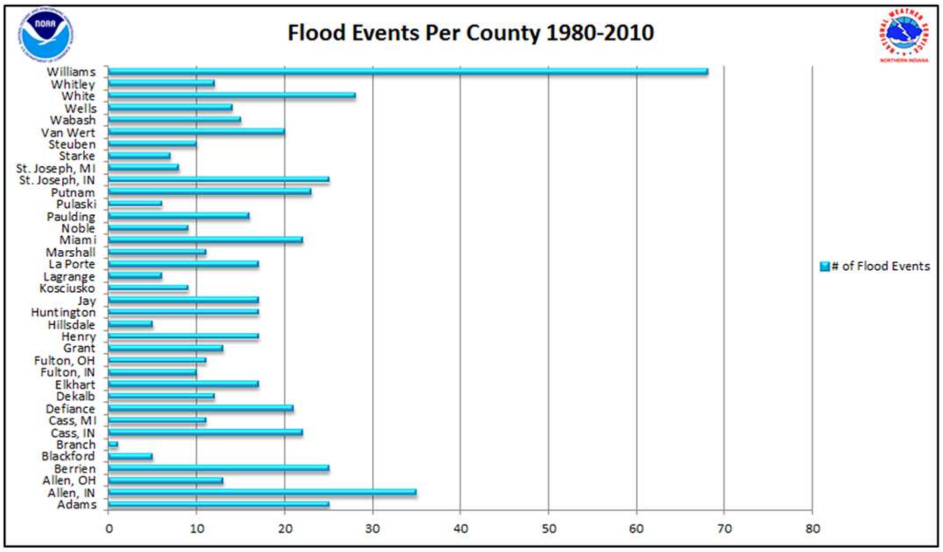


Figure 30. Flood events per county in the KIWX CWA.

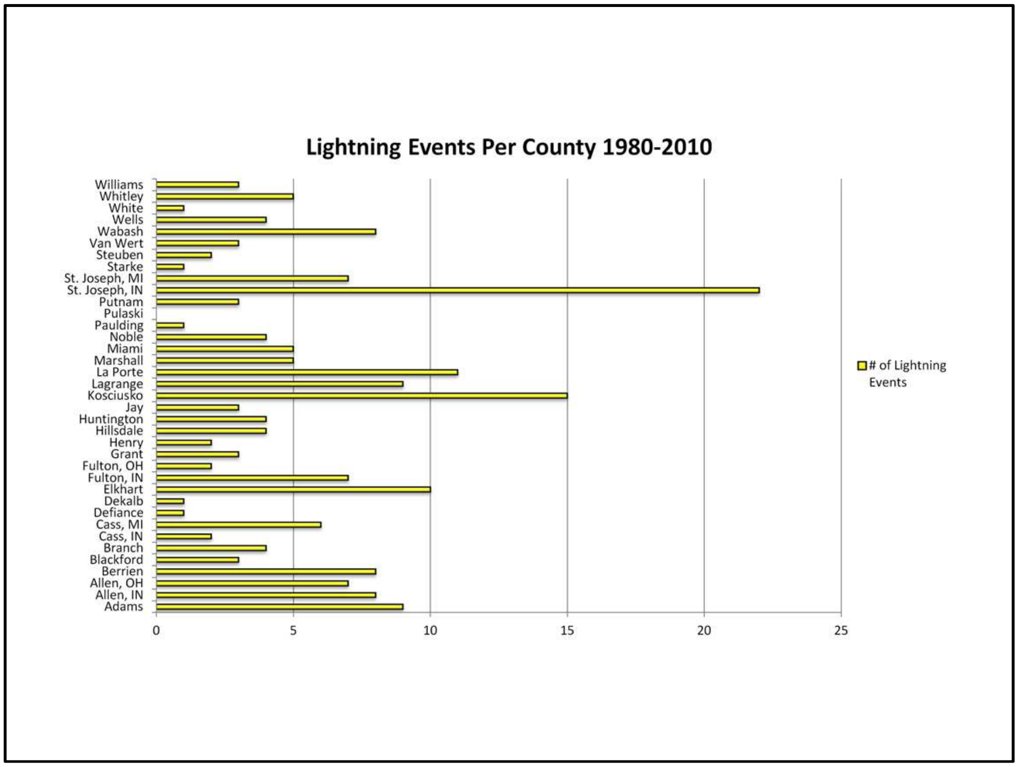


Figure 31. Lightning-related events per county.

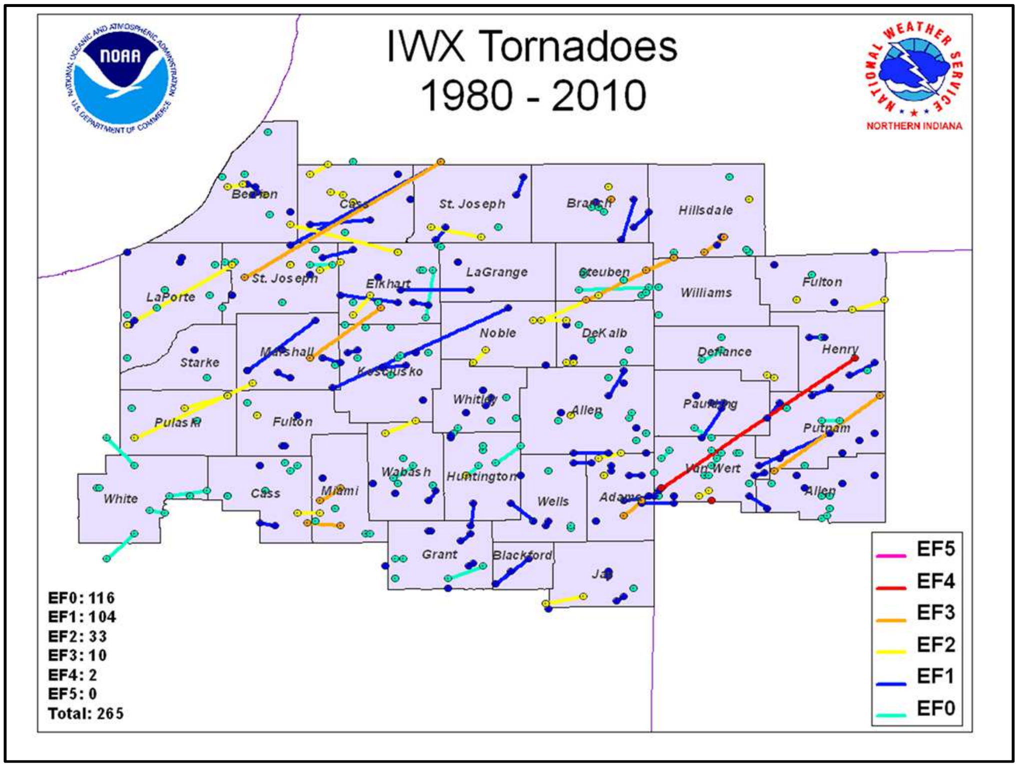


Figure 32. Recorded tornadoes and their strength in the KIWX CWA from 1980 to 2010.

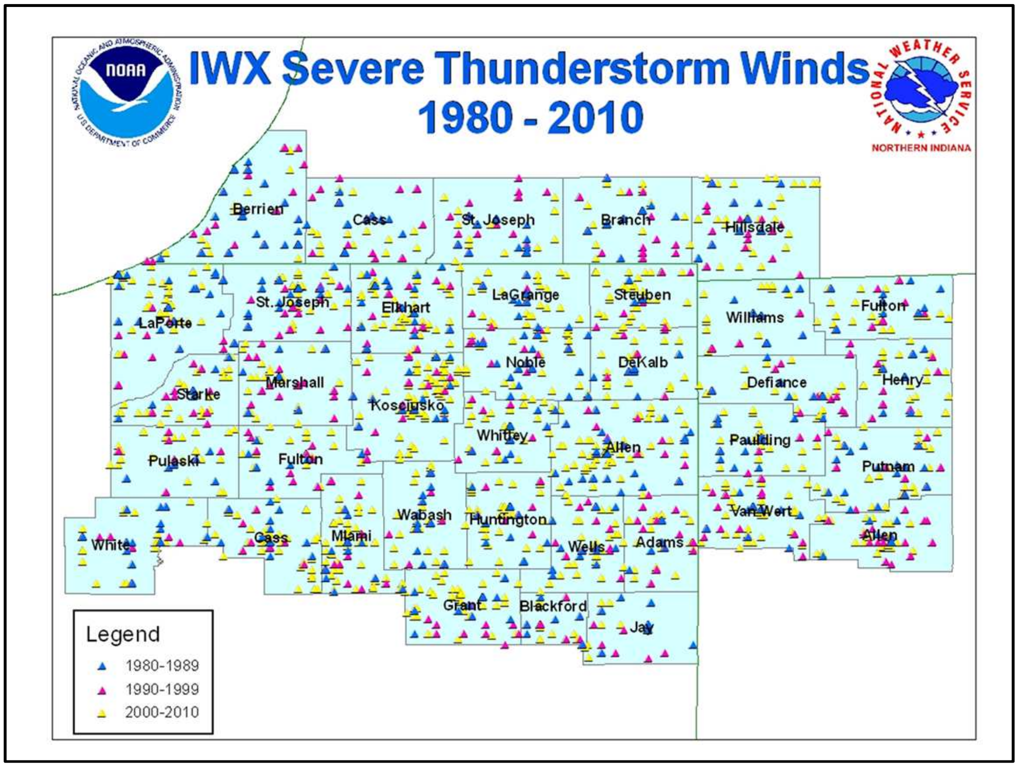


Figure 33. Documented severe thunderstorm wind events in the KIWX CWA from 1980 to 2010.

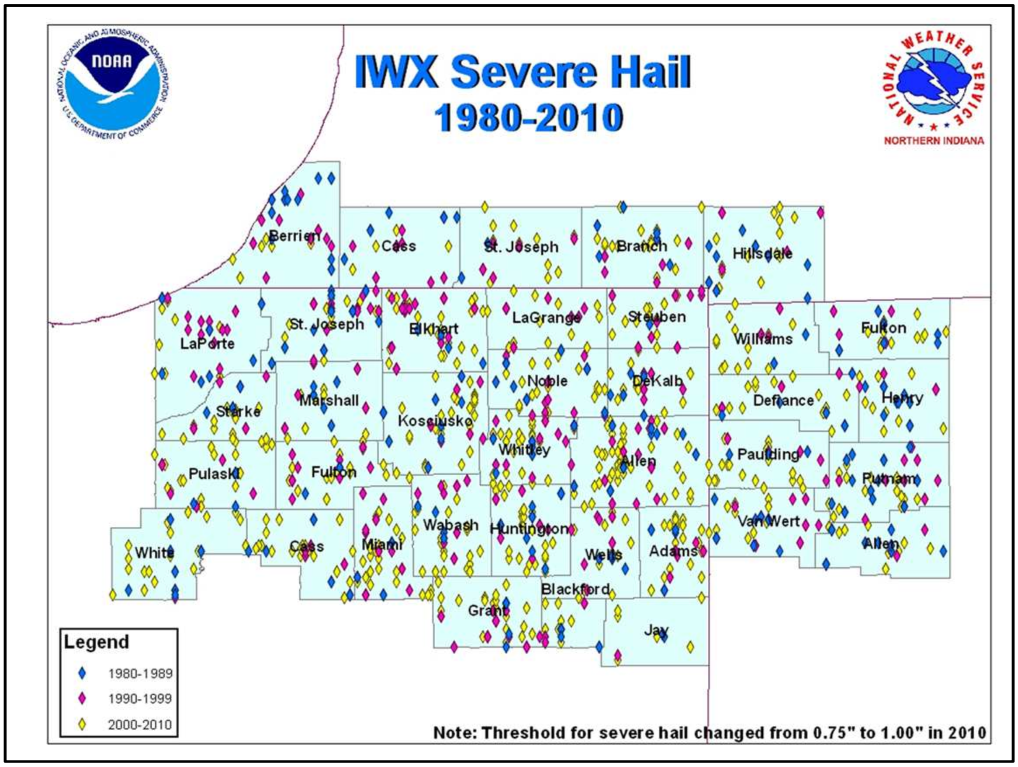


Figure 34. Documented severe thunderstorm hail events in the KIWX CWA from 1980 to 2010.

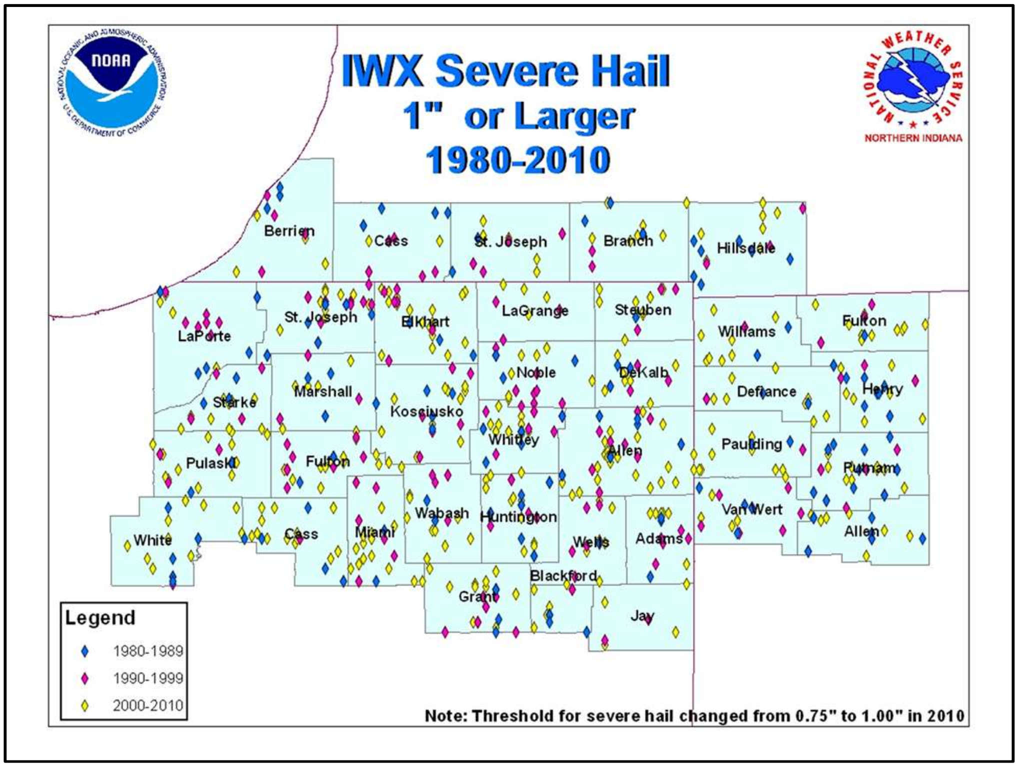


Figure 35. Documented hail events of 1” in diameter or larger in the KIWX CWA from 1980 to 2010.

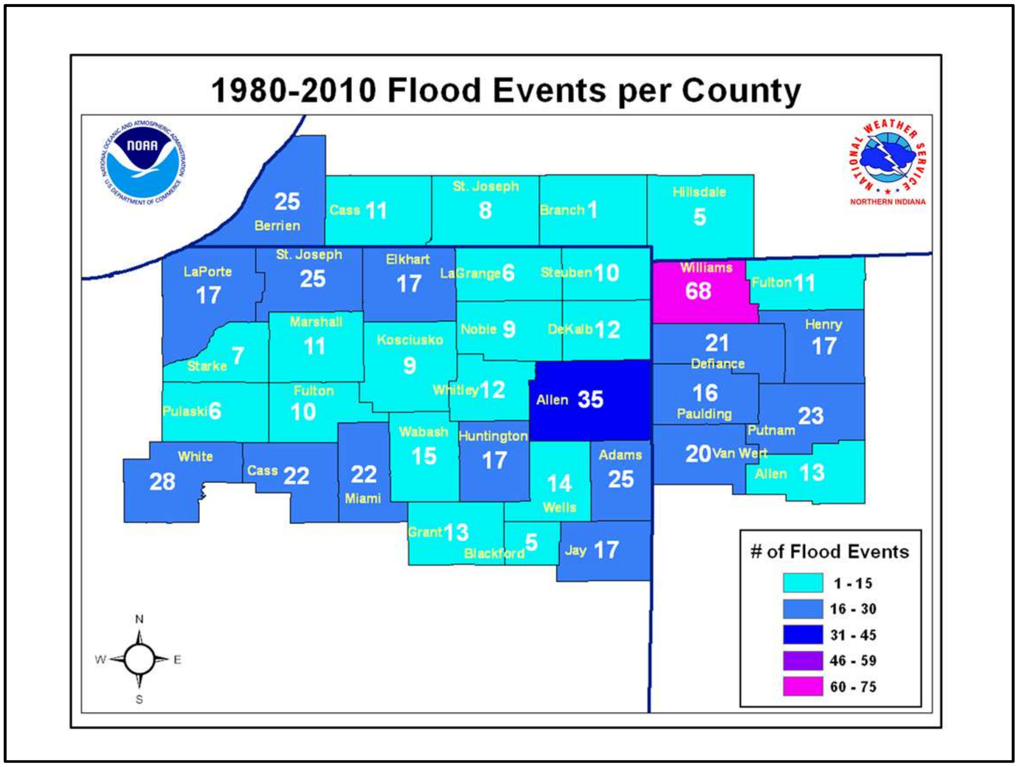


Figure 36. Number of flood events per county in KIWX CWA from 1980 to 2010.