# A COMPARATIVE CLIMATOLOGY OF TORNADO OUTBREAKS & OUTBREAK VARIABILITY IN THE UNITED STATES

by

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ABSTRACT

A COMPARATIVE CLIMATOLOGY OF TORNADO OUTBREAKS AND OUTBREAK VARIABILITY IN THE UNITED STATES

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In the U.S.A., tornado outbreaks contribute to hundreds of fatalities and cause considerable physical and monetary damages annually. Historically, tornadoes, and particularly tornado outbreaks, have been poorly understood in terms of physical processes and spatiotemporal variability. One source of this uncertainty is the lack of an objective definition of "tornado outbreak." The aims of this study were to examine the spatiotemporal variability in historic U.S. tornado outbreaks using different definitions of the term "tornado outbreak." The potential associations between outbreak variability and eastern tropical Pacific SST variability were also investigated. We find that over the period 1975-2014, "Tornado Outbreak Alley" is centered in northern Alabama. Additionally, outbreak activity exhibited increasing trends with time for Winter, Spring, and Fall according to four of five outbreak records. State-level linkages to winter ENSO influences, focused generally in the Southeast, may indicate the tropical Pacific as a forcing factor in U.S. outbreak variability. We demonstrate both the contrasts in outbreak records that result from different definitions of outbreak, and that outbreak activity appears to be increasing, regardless of definition.

# CHAPTER I

## INTRODUCTION

In 2011, an estimated 1700 tornadoes produced 553 tornado-related fatalities in the United States of America (U.S.), making it the deadliest U.S. tornado year since 1936 and the second-highest tornado producing year since 1950 (Fuhrmann et al. 2014). This significant tornado year fostered an increased public awareness of tornado outbreaks and the need for a better understanding of spatiotemporal patterns of such outbreaks to enhance the effectiveness of both outbreak forecasting and tornado alert systems.

Recent findings indicate that between 1973 and 2006, the number of strong tornadoes associated with a tornado outbreak increased by 15 percent, while tornadoes not associated with an outbreak decreased by over 20 percent (Fuhrmann et al. 2014). From this perspective, tornadoes associated with an outbreak represent an increasing proportion of all tornadoes, while singular events comprise a decreasing proportion of the total, emphasizing the need for better understanding of tornado outbreaks (Fuhrmann et al. 2014).

However, these results must be interpreted with caution. “Tornado outbreak” has no formal definition. Rather, individual investigators have defined “outbreak” using different variables and different criteria (Pautz 1969; Galway 1977; Curtis 2004; Fuhrmann et al. 2014). Further, some investigators have chosen outbreak definitions specifically to exclude (or to include) tornado outbreaks associated with landfalling tropical cyclones [TCs; tropical depressions, tropical storms, and hurricanes (McCaul 1991; Curtis 2004; Moore and Dixon 2011)]. However, there is no comprehensive comparative study between U.S. tornado outbreak climatologies based on different published outbreak definitions (Galway 1977; Curtis 2004; Doswell et al. 2012; Fuhrmann et al. 2014).

CHAPTER II

LITERATURE REVIEW

**Defining "Tornado Outbreak"**

A tornado is an intense low pressure characterized by a tightly rotating column of air connected to the cloud based and making contact with the ground (National Weather Service (NWS) 2009). This is a widely-accepted definition; however, there is no consensus on the definition of a "tornado outbreak." Some outbreak definitions are broader than others, and some place greater emphasis on time-clustering or, alternatively, space-clustering.

For example, one definition described a tornado outbreak as a series of tornadoes associated with a single synoptic event (Shafer and Doswell 2010). All tornadoes produced by a single weather system spanning several days and possibly hundreds of kilometers of storm migration would be included as members of a single "tornado outbreak." A definition this liberal risks diluting the term "outbreak" by including singular tornadic events potentially separated in time by days and in space by several hundred kilometers. Broader interpretations of "outbreak" also may not differentiate between TC-related outbreaks and non-tropical (NT) outbreaks (Shafer and Doswell 2010), which may mask potential distinctions between the spatiotemporal characteristics of tornado outbreaks from different storm types.

Another broad definition of an outbreak is five (a "family") or more tornado touchdowns during the lifespan of a single storm (Pautz 1969; Galway 1977). This initial representation can be divided into categories (Pautz 1969):

Small Outbreak: 6-10 tornadoes

Moderate Outbreak: 11-20 tornadoes

Large Outbreak: 20 or more tornadoes

Another more liberal definition defines a minor outbreak as eight or fewer tornadoes, a major outbreak between nine and 24 tornadoes, and a severe outbreak as greater than 24 tornadoes, excluding smaller groupings of five or six tornadoes (McCaul 1991). Other similar variations describe an "outbreak" as 10 or more tornadoes (Galway 1977), focusing only on the number of tornadoes to determine whether an 'outbreak' had occurred. These definitions contain neither spatial nor temporal restrictions, other than their association with a single synoptic system.

A more conservative outbreak definition requires at least six consecutive tornadoes with Fujita scale/ Enhanced Fujita scale (F/EF) ratings of one or greater, in which each successive tornado must form within a 6-hour block from the previous (Fuhrmann et al. 2014), incorporating both a strict intensity and temporal component in identifying outbreaks. Another investigation defined an outbreak as a tornadic event that produces 1.5% of the yearly expected number of tornadoes. This definition only includes events that produced eight or more F/EF1 tornadoes (Verbout et al. 2007).

Some research has explored TC tornado outbreaks, defining a TC tornado outbreak as twenty or more tornadoes in a given TC event (Curtis 2004). Twenty tornadoes is coincidentally also the long-term average number of tornadoes produced per TC in the U.S. (Moore and Dixon 2011). This reflects the wide variation in tornado outbreak behavior between any two landfalling TCs, and also highlights the uncertainty around tornado outbreaks associated with TCs.

**Historic Tornado Reporting**

Until the mid-1970's, inconsistencies in tornado reporting, damage assessment, and intensity estimation led to tornado data inaccuracies and presented serious barriers to historic tornado research (Edwards et al. 2013; Agee and Childs 2014). A key feature of time series of observed tornadoes in the U.S. prior to the mid-1970's is a persistent increasing trend, which is widely agreed to reflect changes in reporting accuracy as opposed to a trend in nature (Edwards et al. 2013; Agee and Childs 2014).

In spite of improved tornado reporting accuracy, some apprehensions remain surrounding the potential overemphasis of the F/EF (Agee and Childs 2014). The main criticism of the F/EF scale results from inconsistency of NWS personnel assessment of damage and wind strength during the F scale's early incorporation in the mid-1900's (Doswell et al. 2009). Over time, the reasoning behind inconsistent rankings shifted considerably towards population bias, structural damage assessments, structural flow, and building codes and enforcement, instead of inconsistencies in NWS personnel assessment (Edward et al. 2013). To account for some inaccuracies in counting and lack of tornado attribute information in tornado records, particularly early records, there have been efforts, using old newspaper reports and photographs, to fill in several pieces of missing information of tornadic events and characteristics (Agee and Childs 2014).

**Spatiotemporal Characteristics of Outbreak Behavior**

There are different spatial categories for NT tornado outbreaks based on tornado counts between 1870 and 1975, including Local, Progressive, and Line (Galway 1977). Local outbreaks are roughly confined to a circular area and do not span beyond a seven-hour period (Galway 1977). A Progressive outbreak consists of tornadoes extending west to east with clear zonal trends (Galway 1977). The difference between the first and last tornado for a progressive outbreak scale can be up to 563 km and as long as nine-and-a-half hours (Galway 1977). A Line outbreak is typically orientated meridionally and lasts an average of roughly eight hours (Galway 1977).

The majority of TC tornadoes occur within 400 km of the coast and begin to develop one to two days before the landfall of the TC center (Schultz and Cecil 2009; Moore and Dixon 2011). In some cases, tornadoes can extend beyond the 'typical' reach of a TC and have been found to extend as far inland as 500-600 km (Spratt et al. 1997; Verbout et al. 2007; Schultz and Cecil 2009). Several researchers even consider tornadoes within 800 km of a TC center to potentially be TC tornadoes and use this value as a liberal filter to identify all possible TC tornadoes (McCaul 1991; Schultz and Cecil 2009). This liberal interpretation, while including all potential TC "tornado outbreaks," makes it difficult to compare TC and NT outbreak events.

In one investigation, outbreaks from 1973 to 2010 were divided into three categories: all outbreaks, strong outbreaks, and weak outbreaks (Fuhrmann et al. 2014). Tornado outbreaks ("all," i.e., tropical and NT) were focused in the northwest corner of Mississippi and the southeast corner of Arkansas (Fuhrmann et al. 2014). Strong Outbreaks, consisting of ≥500 adjusted Fujita miles, tend to concentrate in large portions of Arkansas and northwest Georgia. However, Strong Outbreaks are considerably less frequent than weaker outbreaks.

Investigating seasonality of outbreak behavior between 1973 and 2010, the Midwest and the Southeast experienced a large number of tornado outbreaks and singular tornado events between April and July, compared to other regions of the U.S. (Fuhrmann et al. 2014). The distribution of tornado outbreaks in the Southeast during this time is approximately bi-modal, with the maximum tornado probability in April-July, similar to most of the U.S. Unlike other regions, the Southeast also exhibits a secondary peak between August and early December (Fuhrmann et al. 2014). This is due to tornadoes and tornado outbreaks associated with landfalling TCs along the southeast coast (Fuhrmann et al. 2014).

Between 1921 and 2010, the majority of strong, violent tornadoes (≥F/EF4) touched down in the south-central U.S. (Doswell et al. 2012). Strong tornado days were concentrated in central Oklahoma and eastern Kansas (Doswell et al. 2012). In general, tornadoes associated with TCs are weaker than those associated with NT systems (Verbout et al. 2007; Moore and Dixon 2011).

Other investigators have examined the number of tornado days, the Fujita scale rankings, changes in monthly tornadic activity, changes in the number of outbreak tornadoes, and the changes between singular tornado events versus multi-tornadic events, etc., to better understand tornadic behavior and frequency (Doswell et al. 2012; Brooks et al. 2014; Fuhrmann et al. 2014).

The changes between single tornado-day and multi-tornado-day counts over time, indicate that tornado outbreaks may be linked to larger climate forcing factors (Pautz 1969). For example, El Niño/ Southern Oscillation (ENSO) variability appears to influence both the monthly number of tornadoes and TC-landfall days, probably through the influence on TC landfall probability (Larson et al. 2005).

**Influences of the Southern Oscillation**

ENSO is a leading mode of global ocean-atmospheric influences variability with wintertime influences in the eastern U.S., among other regions (Gershunov and Barnett 1998; Brown and Comrie 2004; Huang et al. 2016). ENSO is considered a driver of several climate anomalies including cool-season temperature and precipitation in the U.S. (Huang et al. 2016).

ENSO typically has a periodicity of between two and seven years and is most commonly measured through sea surface temperatures (SST) and the Ocean Niño Index (ONI) to account for interannual variations (Brown and Comrie 2004; Huang et al. 2016). ENSO variability (SST anomalies in the tropical Pacific) is closely linked to atmospheric changes great distances from the eastern tropical Pacific and is a potential indicator of shifts in tornado outbreak patterns (Huang et al. 2016).

SST measurements identify general anomalies through the creation of a standard value, that identifies deviations from normal temperatures (National Centers for Environmental Information (NCEI) 2017). This baseline, known as ONI, assists in identifying above and below normal standards (warm or cold episodes; NCEI 2017). A warm or cold "episode" is characterized as an observed SST value above five-consecutive three-month running mean. Observed SST values +/-0.5°C above/ below the baseline, identify cold and warm episodes or La Niña/ El Niño events (NCEI 2017).

While ENSO variability is associated with TC formation and thus may be linked with TC tornado outbreaks, ENSO variability can also be associated with NT tornado outbreaks (Verbout et al. 2007; Lee et al. 2013). The Trans-Nino Index, a newer climate index based off of the difference between Niño regions [Nino4, Nino3, Nino 3.4, Nino 1+2 regions], has been interpreted to suggest strong teleconnection patterns that, during a positive phase, increase the upper-level westerlies and lower-level south westerlies over central and eastern U.S., enhancing the environment for tornadic formation (Lee et al. 2013).

**Decadal Changes in Storm Frequency and Intensity**

Over the last half a century, the U.S. averaged roughly 800 weak, 173 strong, and nine violent tornadoes per year (Doswell et al. 2012). During this time, there was an increase in the number of multi-tornado days, but an overall decrease in the total number of tornado days (Doswell et al. 2012; Brooks et al. 2014), suggesting a decreasing trend in the number of single-tornado days. In outbreak events between 1973 and 2010, the number of F/EF1 and stronger tornadoes increased by 15 percent, while singular tornado events decreased more than 20 percent decrease (Fuhrmann et al. 2014).

Examining TCs between 1971 and 2005, there was an increase in the number of TCs that reached Category 4 and 5 (Webster et al. 2005). Stronger TCs have a greater probability of producing tornadoes than weaker TCs (Gentry 1983; Verbout et al. 2007). Examining TCs in the North Atlantic Basin from 1954 to 2004, 78 percent of TCs that produced an outbreak were classified as a Category 2 or higher at landfall (Verbout et al. 2007). Other studies have also concluded that while the relationship is weak due to tornadic variability, there is a statistically significant correlation between TC intensity and TC tornado formations (Moore and Dixon 2011).

The relationship between TC-tornadoes and TC intensity is stronger when examining category 3 TCs; accounting for 60 percent of confirmed TC-tornadoes (Moore and Dixon 2011). Category 3 storms make up 38 percent of landfalling TCs and were associated with eight out of 12 major or severe tornado outbreaks between 1950 and 2005 (Moore and Dixon 2011). The Gulf Coast in particular experiences many TC-tornadoes, 81 percent of which are categorized as weak (F0 and F1) and 18 percent were categorized as strong (F2 and F3; Moore and Dixon, 2011).

Eighty-one percent of TC tornadoes that are associated with the East and Gulf coast are also weaker tornadoes, with shorter path lengths, and lower Fujita scale ratings than non-tropical tornadoes (Verbout et al. 2007; Moore and Dixon 2011). However, on average each TC produces approximately 20 tornadoes whereas NT storms do not produce nearly as many on average (Moore and Dixon 2011). Stronger TC trends could indicate a greater number of TC tornado outbreaks, with substantial financial and social implications.

# CHAPTER III

## RESEARCH OBJECTIVES

The varying interpretations of 'outbreak' leave the climatology of the U.S. tornado outbreaks uncertain and relatively underexplored in the geographic climate science literature. Comparing and contrasting the spatial and temporal properties of outbreak climatologies based on several definitions of the term 'outbreak' could illuminate spatiotemporal patterns in outbreak activity. Where different definitions of outbreak produce similar outbreak histories, we should be able to view the similarities as reflecting reasonable accuracy. Where different definitions produce dissimilar outbreak histories, the differing criteria between the definitions may help explain the differences and aid in relatively objective interpretation. Additionally, identifying potential ocean-atmosphere influences on outbreak variability may improve our understanding of the physical mechanisms that produce multi-tornado events, with possible benefits to planners and disaster relief applications. Thus, my specific objectives were to:

1. Comprehensively describe the history of specific characteristics of tornado outbreaks in the United States since 1975, using different published definitions of tornado outbreak.

    a. Compute the annual and seasonal statistical properties of number of Tornado Outbreaks (TO), number of Outbreak Tornadoes (OT), and the proportion of all tornadoes that were outbreak tornadoes (Outbreak Tornado Proportions; OTP);

    b. Identify spatial and/or temporal patterns in tornado outbreak behavior since 1975;

    c. Document annual and seasonal variability in tornado outbreak behavior between 1975 and 2014; and

2. Identify and record ENSO influences on TO, OT, and OTP;

    a. Examine correlations between ENSO variability and spatiotemporal patterns identified in the outbreak climatologies;

b. Interpret linkages between ENSO variability and outbreak frequency in the context of the known pattern of ENSO influences on seasonal weather.

# CHAPTER IV

# DATA AND METHODS

## Data

### Tornado counts.

I obtained tornado counts through the Storm Prediction Center (SPC) National Severe Weather Database Browser or the SVR Plot 3.0 (SPC 2014). To account for some missing data, I utilized other severe event references to verify the details of the tornadic episodes (SPC 2009; NCEI 2014; NHC 2014; National Oceanic and Atmospheric Administration (NOAA) Central Library 2014; SPC 2014). In some cases, however, the data was unable to be verified and filled in through supplemental data. Specifically, tornado counts proved to have inaccurate or absent information that I could not reference or verify through other means (Figure1). This was usually due to a lack of end coordinates.

To conservatively correct this error, I formally assumed that for all missing tornado path end-coordinates (35 percent of dataset), each start-latitude equals its end-latitude, and I altered the end-longitude by adding 0.01 (degrees) to the start-longitude. Thus, for any tornado with an unknown path, I imputed a small due-eastward movement. This track assumption introduces inaccuracies regarding the behavior of individual tornadoes, although presumably the path coordinates for high-impact tornadoes are less likely to be missing. These potential tornado path errors, especially as confined to relatively small and/or short-lived individual tornadoes (and because only 35 percent of tornadoes lacked these data), should not substantially affect our analyses, which focus primarily on multi-tornado events. Further, given my focus on large-scale variability, analysis of individual tornado characteristics (including path specifics) are beyond the scope of this study.

It was suggested by the Chief of the Forecast Operations Branch within the Weather Prediction Center and dataset steward for these raw datasets to operate under the assumption that each start-latitude equals its end-latitude, and to alter the end longitude by adding 0.01 to the start-longitude; this creates a new, more plausible eastward movement and allows for a more likely and conservative track to be visible on a map. This track assumption may not always be true, since both path width and path length appear to be unaffected by the lack of correct end-coordinates, but this is the most viable option for the parameters and time constraints of this study.

**Definitions of tornado outbreak.**

I created one definition of outbreak, designed to be quite liberal and to capture any possible tornado outbreak that may have occurred. For example, the requirements for an 'outbreak' under this definition were three or more tornadoes in a single calendar day (if an event continued into the next day, at least one tornado must be within eight hours of the last tornado on the previous day), associated with a single synoptic system. I created a relatively loose spatial component, restricting the 'outbreak' to include only tornadoes within 500 km of another tornado within the group. Using the threshold requirements for this "Base outbreak" definition, I analyzed the full daily tornado records for 1975-2014 and identified all tornado outbreaks. I used the resulting baseline tornado outbreak record to compare and contrast against the outbreak records that resulted from applying different, more refined 'outbreak' definitions to the baseline record. I chose the alternative outbreak definitions (Pautz 1969; Galway 1977; Curtis 2004; Fuhrmann et al. 2014) because each has distinct criteria for a multi-tornado event to qualify as an 'outbreak,' reflecting a range of requirements from relatively liberal to relatively conservative. The selected definitions differ in what criteria (e.g., spatial proximity, temporal proximity, number of individual tornadoes) are considered and/or in the qualifying threshold values of given criteria (Table 1)

Curtis's definition of 'outbreak' requires twenty or more TC tornadoes associated with a TC (Curtis 2004). This definition thus relies strictly on tornado counts associated with a single TC, requiring no spatial, temporal, or magnitude component (Table 1).

Galway's definition identifies an 'outbreak' as ten or more tornadoes associated with a single synoptic system (Galway 1977). While this definition also primarily focuses on tornado count, it is more liberal in the number of tornadoes considered to be an 'outbreak,' compared to Curtis's definition. However, like Curtis's definition, this definition considers no spatial, temporal, or magnitude criteria, aside from the association with one storm system (Table 1).

Pautz's definition of 'outbreak' requires a minimum tornado count of five to be considered a 'family' and six or more tornadoes in a calendar day to be considered an "outbreak" (Pautz 1969). This definition has no minimum spatial or tornado intensity components (Table 1).

Fuhrmann's definition identifies an outbreak as a sequence of six or more tornadoes with an F/EF rating of one and greater, and no more than six hours separating any two tornadoes in the outbreak (Fuhrmann et al. 2014). This definition is the strictest definition of the group with tornado count, temporal, and magnitude restrictions, although it has no explicit spatial restrictions (Table 1).

**ENSO data.**

I retrieved monthly SST anomaly data for the period 1975-2014 for the Nino 3.4 region (Huang et al. 2016; Climate Prediction Center (CPC) 2017). I computed annual and seasonal averages, using boreal astronomical seasons (i.e., DJF, MAM, JJA, and SON). I calculated the full-period mean (1975-2014) for each season and each year. I then derived my ENSO anomaly series by computing the time series of seasonal and annual SST anomalies (relative to the respective mean value for the full period 1975-2014.

The ENSO anomaly time series I created is correlated to the Niño3.4 SST anomaly series at r=0.991. This is expected, as the main difference between my Niño region SST anomaly series and the Niño3.4 SST anomaly series is the slight different baseline period from which the seasonal means are calculated. Hereafter, this time series is termed “ENSO variability.”

**Data Analyses**

Overall, the five definitions range from liberal to conservative, with the most conservative definition retaining a strict temporal and intensity component and the most liberal retaining only a (relatively) low tornado count component (Pautz 1969; Galway 1977; Curtis 2004; Fuhrmann et al. 2014; Table 1).

From the complete tornado dataset (>40,000 individual tornadic events) and for both annual and seasonal time scales I calculated, based on the different criteria in each “outbreak” definition, preliminary descriptive statistics including number of tornado outbreaks per year and season, average number of outbreaks per year and season, number of outbreak tornadoes, and the proportions of all tornadoes that were part of an “outbreak.” From the available variables, I chose to analyze Tornado Outbreak (TO), Outbreak Tornadoes (OT), and Outbreak Tornado Proportions (OTP). These three variables characterize outbreak behavior in three different ways; as a group (all outbreaks), as individuals (all outbreak-related tornadoes), and in relation to non-outbreak events (OT as a proportion of all tornadoes).

I analyzed spatial patterns of OT frequencies for each definition using a kernel density analysis (Howe et al. 2014; Calligaris et al. 2017). Kernel density analysis allows estimation (and mapping) of the probability density function of a random variable using gridded coordinate points for spatial reference (e.g., Rosenblatt 1956). I categorized the probability density function using a Natural Breaks classification of OT frequencies for the Base definition (the Base definition had the largest range of density estimates). I then forced the Natural Break categories from the Base outbreak record onto the probability density function results for each of the other outbreak records. One drawback of this method for mapping purposes is that the probability density functions of TO and OTP cannot be accurately estimated, as an outbreak (regardless of definition) is not bounded by objective coordinate points, and OTP is not logically connected to any coordinate points. However, for OT, I mapped the spatial probability density functions for comparison across time and between definitions.

To identify a potential ENSO influence on outbreak behavior, I used Spearman correlation between the time series of annual and seasonal ENSO variability and the respective annual and seasonal variability of TO, OT, and OTP. I also examined these relationships for OT and OTP by state to isolate regional or sub-regional variability (or change over time) in the ENSO influence.

# CHAPTER V

# RESULTS & DISCUSSION

## Annual Spatiotemporal Variability

### Tornado Outbreaks (TO).

For the entire study area (continental U.S.A.), the five selected outbreak definitions produced highly varied outbreak histories for TO. Annual average numbers of TOs by definition ranged from 85 (Base definition) to as low as nine (Curtis definition; Table 2). The outbreak records based on the Base, Curtis, Galway, and Pautz definitions all exhibited significant increases over time, while the Fuhrmann outbreak record indicated no significant temporal trend (Table 2).

### Outbreak Tornadoes (OT).

For the full study area, annual outbreak records for OT vary considerably between definitions, with a maximum annual average OT of 840 (Curtis definition) and a minimum annual average of 262 (Fuhrmann definition; Table 2). Additionally, as with the TO records, the OT record for each definition except Fuhrmann's exhibits a significant increase with time (Table 2).

At the state (i.e., sub-regional) level, for all definitions except Fuhrmann's, reasonably consistent spatial patterns of variability between definition included maximum increasing OT trends along the U.S. Mid-Atlantic and Gulf of Mexico coasts, as well as in states more closely aligned with the traditional U.S. "Tornado Alley" (Arkansas, Missouri, Iowa, Oklahoma, and Nebraska; Figure 2a, b, c, d, e).

For all definitions, OT frequencies were greatest in the southeastern U.S., and specifically in Mississippi, Alabama, and Arkansas, although variations in OT frequency between definitions are more pronounced in areas with lower overall OT (Figure 3). Viewed in five-year increments (Figure 4-8), the increasing trend identified by correlation analysis is evident for each outbreak definition, with maximum expression in the most recent five- and 10-year periods (Figure 4-8 g, h). For all definitions, the Southeast is the highest-frequency region for OT throughout the 40-year record.

**Outbreak Tornado Proportions (OTP).**

For the entire study area, the maximum annual average OTP was 87% (Base definition) and the minimum annual average was 25% (Fuhrmann definition; Table 2). As with TO and OT, the OTP record for each definition except Fuhrmann exhibited a significant increase with time (Table 2).

At the state level, for all definitions except Fuhrmann, I identified consistent increasing trends in OTP along the U.S. Mid-Atlantic and the Gulf of Mexico coasts, as well as in states that are typically aligned with the traditional U.S. "Tornado Alley" (Texas, Oklahoma, Nebraska, Iowa, Arkansas, Illinois, and Indiana; Figure 2). Alternatively, the Fuhrmann outbreak record indicated significant decreases in OTP in a small group of midwestern states (Texas, Colorado, and Wyoming), and two northern interior states (Wisconsin and Michigan; Figure 2 j). According to Fuhrmann's outbreak definition, only one state (Kentucky) exhibited significant increases in OTP with time.

**Discussion.**

Between outbreak variables there is considerable variation between definition results. However, despite the differences, there is a significant increase over time in all three variables for all definitions, excluding Fuhrmann. The Fuhrmann outbreak record is consistently an outlier for each outbreak variable. This is likely because Fuhrmann's definition excludes F/EF0 tornadoes, while other definitions do not. This resulted in fewer qualifying TC tornadoes, fewer identified TO and OT, and thus lower OTP values according to Fuhrmann's definition. Fuhrman's definition substantially reduces the OTP value in particular by increasing the denominator to include all F/EF0 tornadoes. This notable variation in OTP between Fuhrmann's definition and other definitions raises interesting questions regarding the relationship between tornadic intensity and outbreak behavior with time.

Comparing OT frequencies and state level OT trends (Figures 2 & 3), the Southeast and some portions of the Midwest emerge as general focal points of the highest OT frequencies as well as significant increasing trends over time, for the Base, Curtis, Galway, and Pautz outbreak records. The concentration of outbreak behavior in the Southeast is less evident in the Fuhrmann outbreak record. Again, the exclusion of F/EF0 tornadoes from consideration in the Fuhrmann definition probably explains this difference. In the Southeast, TCs produce relatively high tornado numbers on average (Curtis 2004; Moore and Dixon 2011). The majority of these TC-related tornadoes are weak (F/EF0 or F/EF1; Verbout et al. 2007). Therefore, the exclusion of the weakest tornadoes from the outbreak definition likely excludes a substantial portion of TC tornadoes, which, in the U.S., primarily affect the Southeast. This indicates that for all tornado outbreaks (including the weakest tornadoes), the Southeastern U.S. around northern Alabama was a relative hotbed of outbreak activity during 1975-2014. However, it appears that substantial proportions of the individual OTs in this region were weak (F/EF0), and thus the Fuhrmann record indicates notably less overall outbreak activity in the Southeast, especially near the coast.

## Seasonal Spatiotemporal Variability

### Tornado Outbreaks (TO).

For the entire study area, Winter TO averages range between a maximum of six (Base definition) and a minimum of one (Curtis definition; Table 2). Spring average TO ranges between 32 (Base definition) and five (Curtis definition; Table 2). Summer average TO range is 36 TO (Base definition) to three TO (Curtis definition; Table 2). The Fall average TO range is 11 TO (Base definition) to one TO (Curtis definition; Table 2).

For the full study area, Winter and Fall TO increased with time for all definitions (Table 2). However, only two outbreak records indicated significant Spring increases with time (Curtis and Galway), and only the Pautz record exhibited a significant summer increase with time (Table 2).

### Outbreak Tornadoes (OT).

For the full study area, Winter OT records varied between definitions with a maximum average OT of 63 (Base definition) and a minimum average OT of 28 (Fuhrmann definition; Table 2). Springtime averages for OT ranged between 392 (Base definition) and 144 (Fuhrmann definition; Table 2). Averages for OT for Summer ranged between 271 (Base definition) and 50 (Fuhrmann definition; Table 2). Fall averages for OT ranged between 114 (Base definition) and 41 (Fuhrmann definition; Table 2).

Additionally, OT records for both Winter and Fall exhibit a significant increase with time for all definitions (Table 2). Springtime OT records indicate a significant increase with time for all definitions, excluding Fuhrmann. OT records for Summer show only an increase with time for Pautz's definition (Table 2).

At the state level, seasonal variability was evident and broadly consistent between definitions (Figure 9). The clearest state level trends occurred in Winter across much of the Southeast and portions of the Ohio Valley, indicating an increase in OT with time (Figure 9 a, b, c, d, e). Fuhrmann's definition also indicates an increase in OT with time in Winter, but only in some states within or near the Ohio valley (Missouri, Illinois, and Kentucky). Fall records exhibit a concentration of OT behavior in the Southeast/Ohio Valley, but this pattern is not consistent between definitions (Figure 9 p, q, r, s, t).

State level OT groupings during for Spring (Figure 9 f, g, h, i, j) indicate an increasing trend in the Southeast and in some states more closely aligned with the traditional U.S. "Tornado Alley" (Colorado, Nebraska, Kansas, Iowa, Illinois). While there is more Springtime variation between definitions than in Winter, the general expansion of outbreak activity from the Southeast westward is evident in all outbreak records, including Fuhrmann. The Fuhrmann record for Springtime outbreak behavior is distinct from the other definitions both in the low number of states with increasing outbreak trends, and in its lack of any clear regionalization of the trends that do appear. Additionally, Fuhrmann is the only outbreak record that exhibited a (state-level) decrease in OT during the spring season (Texas; Figure 9 j).

Few states exhibited a time trend in outbreak activity during the summer season. States with significant increases/decreases in OT with time are widely spread, with a general tendency towards northern states (Figures 4-8, Figure 9 k, l, m, n, o). Fuhrmann's definition identifies zero states with significant increases, and strong decreasing OT trends in Colorado, Wyoming, Michigan, and New Jersey. All other definitions identify only increasing OT trends with time, with one exception (Base definition indicates a decrease in OT in Michigan).

During the Winter the Southeast and particularly the Gulf of Mexico coast have high OT frequencies, particularly in northeast Arkansas and northern Alabama (Figures 4-8, Figure 10 a, b, c, d, e). During Spring, those high frequency areas expand northward and eastward towards the Atlantic coast and the Midwest, including traditional "Tornado Alley," states, covering a larger portion of the U.S. (Figure 10 f, g, h, i, j). During Summer, the highest-frequency areas migrate to Iowa, South Dakota, Minnesota, Kansas, and Illinois (Figure 10 k, l, m, n, o). Fall indicates a return of high OT frequencies to the Southeast, the Gulf of Mexico coast, and the Ohio Valley, resembling the spatial pattern of OT frequency for Winter (Figure 10 p, q, r, s, t).

**Outbreak Tornado Proportions (OTP).**

For the entire study area, the maximum Winter average OTP was 73% (Base definition), and the minimum average was 24% (Curtis definition; Table 2). As with TO and OT, the OTP record for each definition. Springtime outbreak records for OTP have a maximum average of 85% (Base definition) and a minimum average of 30% (Fuhrmann definition; Table 2). Summer outbreak records for OTP have a maximum average of 67% (Base definition) and a minimum average of 12% (Fuhrmann definition; Table 2). Fall outbreak records for OTP have a maximum average of 71% (Base definition) and a minimum average of 25% (Curtis and Fuhrman definitions; Table 2).

Additionally, OTP records for Winter, Spring, and Fall all exhibit a significant increase with time, for all definitions except for Fuhrmann. OTP records for Summer exhibit an increase with time for the Base and Pautz definitions, and a decrease with time for Fuhrman's definition.

At the state level, for all definitions except Fuhrmann, I identified consistent increasing Winter trends in OTP for the Southeast and Ohio Valley (Figure 11 a, b, c, d, e). The Fuhrmann record exhibited an increasing trend for only three states (Missouri, Illinois, and Kentucky), the same three identified for Fuhrmann's record for OT. Fall reflects a similar sub-regionalization in the Southeast/ Ohio Valley, but with less consistency between definitions (Figure 11 p, q, r, s, t). The Fuhrmann record for Fall only identifies two states with an increasing trend (Kentucky and South Dakota). During Spring, all definitions except for Fuhrmann have an increasing trend in OTP for the Midwest, portions of the Ohio Valley, and the Southeast. Fuhrmann's definition has a decreasing trend with OTP, isolating Texas, Louisiana, and Missouri, and has an increasing trend in OTP with Tennessee (Figure 11 f, g, h, i, j).

Few states exhibited a trend in outbreak activity during the summer season (Figure 11 k, l, m, n, o). States with significant increase/decrease in OTP with time were widely spread, with a general tendency towards northern states. The Fuhrmann record identifies zero states with significant increasing trends, contrasted against strong decreasing OT trends in Colorado, Wyoming, Michigan, and New Jersey. All other definitions identify only increasing OT trends.

**Discussion.**

By each of the three-selected metrics, outbreak activity was most frequent in Spring. This is not surprising and agrees with basic climatological understanding. Winter and Fall exhibit similar averages in OTP and OT, but Fall values are higher than Winter in each outbreak record. Summer averages exhibit the minimum OTP for all definitions, indicating that from over the period of study, Summer tornado activity was less frequently outbreak-related and more often involved individualized tornadic events.

For the entire study area, all outbreak variables exhibited increasing trends in Winter, except for OTP in the Fuhrmann record. During Spring, time-trends are less prevalent and less spatially coherent. This could be the result of the climatological maximum of tornado activity in this season. The relatively low average outbreak frequencies in other seasons are more susceptible to large increases than are the relatively large outbreak frequencies that already exist for the Spring.

Summer trends are more varied and scarce than in other seasons. The Pautz record exhibited a positive trend in all variables, while for OTP, the Fuhrmann record exhibits the only significant negative trend for the season. All Fall variables exhibited an increasing trend, except the Fuhrmann OTP record, which had no significant trend.

Both OT and OTP at the state level indicate strong concentrations in the Southeast during Winter and Fall. Spring outbreak variables OT and OTP, as in Winter, also indicate concentrations in the Southeast, as well as the Mid-Atlantic and Midwest. Summer trends are not significant for any of the three variables. Summer OT frequencies are maximized in several northern interior U.S. states (Minnesota, Michigan, Iowa, North Dakota, and South Dakota). No other season exhibits outbreak behavior trends in the northern interior of the U.S.

In OTP state level trends, Fuhrmann's record exhibited a significant negative trend for Summer in Colorado, Wyoming, Michigan, and New Jersey. This clearly contrasts with the prevalence of increasing trends in the rest of the outbreak records. This may suggest changes in OT intensity over time. While Fuhrmann's definition excludes all F/EF0 tornadoes, and classifies them as non-OT, this suggests either the number of F/EF1+ tornadoes is decreasing and/or the number of F/EF0 tornadoes is increasing, either reducing the numerator value or inflating the denominator value of the proportion. Fuhrmann's record also exhibits a significant negative trend in OT. Based on the agreement between the Fuhrmann OT and OTP trends for Summer, I posit that the number of F/EF1+ tornadoes is decreasing. However, the logically related question of whether F/EF0 tornadoes occurred with increasing frequency during 1975-2014 is beyond the scope of this study and deserves further attention.

## Annual ENSO Variability

### Tornado Outbreaks (TO).

For the full study area, there were no significant associations between annual TO and annual ENSO variability (Table 2).

### Outbreak Tornadoes (OT).

For the full study area, there were no significant associations between annual OT and annual ENSO variability (Table 2). At the state level, there were few consistencies between definitions (Figure 12 a, b, c, d, e). Two outbreak records (Curtis and Galway) indicated a significant negative association between OT and ENSO variability for California, while two other records (Base and Pautz) indicated a significant positive association between OT and ENSO variability for Texas. There were no significant associations between ENSO variability and the Fuhrmann outbreak record.

### Outbreak Tornado Proportions.

For the full study area, annual outbreak records for OTP exhibited no significant association with ENSO variability (Table 2). At the state level, only three definitions exhibited any association between annual OTP and ENSO variability, but there were no cohesive spatial groupings (Figure 12 g, h, j). The Curtis and Galway definition both indicated a negative association between OTP and ENSO variability for California. The Fuhrmann definition indicated a negative association between OTP and ENSO variability for Alabama.

### Discussion.

There are few identified associations between annual ENSO variability and outbreak behavior, most of which are not consistent between definitions. Because of the absolute infrequency of California tornadoes, the associations between California outbreak variables and

ENSO variability may be spurious. However, the repeated nature of that finding using different outbreak records indicates it may deserve further attention.

The positive association (in two outbreak records) between ENSO variability and annual OT in Texas implies that warm events in the eastern tropical Pacific (El Niños) could force increased tornado activity in Texas. This could be via the influence of ENSO on upper-level westerlies in North America (Brown and Comrie 2004) in which winter storms tend to be more frequent and more vigorous at lower latitudes in the eastern U.S. during El Niño winters. However, the general reduction in Southeast U.S. TC landfalls during El Niño events (Verbout et al. 2007) indicates that if Texas experiences more outbreak activity during these events, the outbreaks are less likely to be associated with a TC, and thus more likely associated with mid-latitude cyclonic storms.  Conversely, due to the infrequency and inconsistency between definitions and the association between each outbreak variable and ENSO variability, those relationships that are present, may be without causation.

## Seasonal ENSO Variability

### Tornado Outbreaks (TO).

For the full study area, there were no seasonal associations between TO and ENSO variability for Spring, Summer, and Fall, for all definitions (Table 2). For Winter, both Curtis and Fuhrmann definitions exhibited a negative association between TO and ENSO variability (Table 2).

### Outbreak Tornadoes (OT).

For the entire study area, the association between OT and ENSO variability exhibited no significant association for Spring, Summer, or Fall for any definition (Table 2). For Winter, all outbreak records except the Base record (not significant) showed a significant negative association between OT and ENSO variability (Table 2).

At the state level, I identified a strong negative association between Winter OT and ENSO variability in the Southeast (Kentucky, Tennessee, Alabama, Arkansas, Mississippi, Illinois, and Indiana), for all definitions, including Fuhrmann (Figure 13 a, b, c, d, e). There is more Spring variation between definitions and a possible concentration of activity in the Mid-Atlantic coast and Southeast regions (Figure 13 f, g, h, i, j). OT and ENSO variability are negatively associated for North Carolina, Georgia, West Virginia, and Louisiana. The Curtis definition exhibits no significant association between OT and ENSO variability (Figure 13 j).

Few states exhibited an association between outbreak activity and ENSO variability during the summer season (Figure 13 k, l, m, n, o). States with significant positive associations were widely spread. The Fuhrmann and Galway records indicated a positive association for Texas and Kentucky (Figure 13 m, o). The Base and Pautz records indicate a positive association for Colorado and Kentucky (the Base definition also includes Washington state; Figure 13 k, n,). The Curtis record exhibited no associations between OT and ENSO variability (Figure 13 l). Fall exhibits few associations between OT and ENSO variability (Figure 13 p, q, r, s, t). Both Curtis and Galway definitions, have no associations between OT and ENSO variability (Figure q, r). There are no recognizable spatial concentrations for all other definitions.

**Outbreak Tornado Proportions (OTP).**

For the entire study area, Winter exhibits negative associations between OTP and ENSO variability for all definitions, including Fuhrmann (Table 2). During the Spring, only the Fuhrmann definition exhibits a negative association between OTP and ENSO variability (Table

2). I identified no significant associations between OTP and ENSO variability for Summer or Fall for any outbreak record (Table 2).

At the state level for Winter, I identified a strong negative association between OTP and ENSO variability in the Southeast (Indiana, Illinois, Alabama, Kentucky, Tennessee) for all definitions, excluding Fuhrmann (Figure 14 a, b, c, d, e). The Fuhrmann definition only exhibits a negative association between OTP and ENSO variability, in the Ohio Valley.

State level OTP grouping for Spring have considerable variation between definitions, and vague Mid-Atlantic sub-regionalization for Pautz, Galway, and Fuhrmann definitions (Figure 14 f, g, h, i, j). Pautz, Galway and Fuhrman definitions all exhibit negative associations between OTP and ENSO variability for North Carolina, South Carolina, Kentucky (Figure 14 m, n, o). The Fuhrmann definition also shows a negative association for a few Midwest states (Kansas and Wyoming). The Base definition is the only definition that exhibits a positive relationship between OTP and ENSO variability (South Dakota; Figure 14 f). There is no significant association between the Curtis definition Spring OTP and ENSO variability.

Summer for Galway and Fuhrmann, exhibit significant positive associations for two states (Kentucky and Texas; Figure 14 m, o). Curtis and Pautz's records identify zero states with significant associations between OTP and ENSO variability (Figure 14 l, n).

Few states exhibited an association in outbreak activity during the fall season (Figure 14 p, q, r, s, t). The Fuhrmann and Pautz records show positive associations between OTP and ENSO variability for Louisiana (Figure s, t), while the Base and Pautz records exhibit a positive association for Mississippi and a negative association for Utah (Figure 14 p, s).

**Discussion.**

The absence of a consistent or large-scale ENSO signal in the annual outbreak records and the records for Summer and Fall is not unexpected, as ENSO variability has its strongest influences on North American weather in the winter season (Brown and Comrie 2004). The state-level outbreak associations with ENSO variability are strongly restricted to the Winter and (to a lesser degree) Spring seasons. The significant negative association between the full study area outbreak record and ENSO variability actually reflects significant and strong negative associations concentrated in the south-central part of the U.S.

Across outbreak records, the states with negative Winter outbreak associations with ENSO are relatively consistently clustered in the Midwest and western Gulf Coast regions. Thus, outbreak activity in those areas appears to be suppressed by El Niño conditions, probably due to an unfavorable setting for tornadogenesis that results from increased upper-level ridging over the region(s) related to a deepening downstream trough associated with average El Niño winters. However, winter trends should be viewed with caution due to low overall numbers of observations. Interestingly, the locations with significant negative associations with ENSO variability for Spring are less clustered but consistently farther east than the locations with Winter ENSO associations. Again, this is likely due to the ENSO influence on Winter upper-level winds over North America. The change in ENSO linkages from Winter to Spring could reflect the relative decrease in ENSO forcing during Spring or could reflect "memory" in the form of lagged effects of an El Niño Winter and its associated upper-level flow anomalies.

# CHAPTER VI

# CONCLUSIONS

From the best available U.S. tornado data set covering 1975-2014, I created five distinct records of U.S. tornado outbreak variability, including one "control," record and four records created from the raw data by applying the specific unique criteria applied by earlier investigators. I measured 'outbreak activity' by analyzing the variability TO, OT, and OTP, for both the continental U.S. as a whole, and by individual state. A key finding is that when excluding individual tornadoes from consideration, the geographic picture that emerges is that the U.S. "Tornado Outbreak Alley" is centered in northern Alabama, hundreds of miles from classic "Tornado Alley." This has implications for a wide range of resource and property managers, as well as the general population, in the Southeast. It also raises interesting questions for consideration by the climatological community.

For the entire study area, all three outbreak variables exhibited increasing trends over time for Winter, Spring, and Fall according to four of the five records. Outbreak variables exhibited virtually no trend for the Summer season. However, the length of the record (40 years) precludes firm conclusions about these trends. The general increase corresponds conceptually to increases in Northern Hemisphere average surface air temperatures during the same time period, but it also could reflect the rising limb of some unknown cycle of U.S. tornado outbreak activity with a periodicity of ≥ 80 years, or even internal random (stochastic) atmospheric variability. Further investigation is needed to solidify our understanding of temporal changes in outbreak behavior, but my results provide a preliminary indication that changes are afoot.

I also examined the influence of ENSO variability on annual and seasonal outbreak activity. The weather and climate influences of ENSO variability are well-documented, and logically indicated that ENSO could influence atmospheric processes associated with tornado outbreaks. However, my analyses indicated that, for the limited time frame analyzed, and for the specific ENSO variability record I used, tornado outbreak variability in the U.S. is not strongly driven by ENSO variability, at least for the concurrent season. The significant state-level linkages to winter ENSO indicate that tropical Pacific forcing may play a role in U.S. outbreak variability, but my analyses imply that the signal may be weak, where it exists at all.

Between different definitions, there are relatively few consistencies. It is clear that the choice of definition (i.e., criteria) can substantially impact the resulting story of U.S. tornado outbreak history. The Fuhrmann outbreak record remained a clear outlier for most results. As the only definition that utilized a minimum tornado intensity requirement, the Fuhrmann OTP record differed substantially from the other records, suggesting that in some areas F/EF1+ tornadoes may be decreasing over time, and/or that F/EF0 tornadoes are increasing over time. This likely accounts for the several inconsistencies between the Fuhrmann outbreak record and the others, and represents a fundamentally important question that deserves further research. Other valuable avenues of future inquiry include: examining the potential influence(s) of other features of the ocean-atmosphere system, such as North Atlantic SSTs and the behavior of the Bermuda High; evaluating the potential lag effect between seasonal ENSO variability and seasonal outbreak activity; and, because the Southeast consistently emerged as a hotbed for outbreak activity, examining the similarities and differences in the statistical properties and the potential climatic forcing mechanisms of TC-related versus non TC-related tornado outbreaks.

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flag=1&t01=0&t02=5&t03=0&t04=9999&t05=0&t06=9999&t07=0&t08=9999&t09=0&t10=9999&h01=0&h02=9999&w01=0&w02.

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Table 1: Selected outbreak definitions and their respective minimum qualifying criteria.

| Definition Name | Tornado Number | Distance | Time | Tornado Rating |
|---|---|---|---|---|
| Base Definition | ≥3 | ≤500km | 1 day (within 8-hours, if it crosses days) | NA |
| Curtis Definition | ≥20 | NA | Associated with a Synoptic System | NA |
| Galway Definition | ≥10 | NA | Associated with a Synoptic System | NA |
| Pautz Definition | ≥6 | NA | Associated with a Synoptic System and within a given day | NA |
| Fuhrmann Definition | ≥6 | NA | 6-hours | F/EF1+ |

Table 2: **Statistical results**. Different outbreak records (definitions) are listed in columns; variables (Tornado Outbreak (TO), Outbreak Tornado (OT), and Outbreak Tornado Proportion (OTP) are listed in rows. Blank cells represent non-significant associations.

**p* < 0.05 (2-tailed)

***p* < 0.01 (2-tailed)

| | Variables | Base definition | Curtis definition | Galway definition | Pautz definition | Fuhrmann definition |
|---|---|---|---|---|---|---|
| | **Averages** | | | | | |
| | Tornado Outbreak (TO) | 85 | 9 | 24 | 50 | 18 |
| | Outbreak Tornadoes (OT) | 840 | 351 | 548 | 724 | 262 |
| **Annual (Year)** | Outbreak Tornado Proportions (OTP) | 0.87 | 0.3 | 0.49 | 0.66 | 0.25 |
| | **Trend (Spearman Bivariate Correlation)** | | | | | |
| | TO | 0.326* | 0.668** | 0.623** | 0.455** | |
| | OT | 0.676** | 0.722** | 0.710** | 0.680** | |
| | OTP | 0.808** | 0.720** | 0.774** | 0.784** | |
| | **Averages** | | | | | |
| | TO Winter | 6 | 1 | 2 | 3 | 2 |
| | OT Winter | 63 | 29 | 44 | 55 | 28 |
| | OTP Winter | 0.73 | 0.24 | 0.45 | 0.6 | 0.31 |
| | | | | | | |
| | TO Spring | 32 | 5 | 11 | 21 | 10 |
| | OT Spring | 392 | 199 | 291 | 355 | 144 |
| | OTP Spring | 0.85 | 0.4 | 0.6 | 0.75 | 0.3 |
| | | | | | | |
| | TO Summer | 36 | 2 | 7 | 19 | 4 |
| | OT Summer | 271 | 71 | 135 | 215 | 50 |
| | OTP Summer | 0.67 | 0.16 | 0.31 | 0.52 | 0.12 |
| | | | | | | |
| | TO Fall | 11 | 1 | 3 | 6 | 3 |
| | OT Fall | 114 | 51 | 77 | 99 | 41 |
| **Seasonal (Year)** | OTP Fall | 0.71 | 0.25 | 0.43 | 0.59 | 0.25 |
| | **Trend** | | | | | |
| | TO Winter | 0.384* | 0.542** | 0.482** | 0.408** | 0.362* |
| | OT Winter | 0.515** | 0.536** | 0.506** | 0.486** | 0.352* |
| | OTP Winter | 0.477** | 0.555** | 0.472** | 0.430** | |
| | | | | | | |
| | TO Spring | | 0.510** | 0.418** | | |
| | OT Spring | 0.500** | 0.598** | 0.541** | 0.523** | |
| | OTP Spring | 0.673** | 0.575** | 0.634** | 0.690** | |
| | | | | | | |
| | TO Summer | | | | 0.361* | |
| | OT Summer | | | | 0.340* | |
| | OTP Summer | 0.447** | | | 0.452** | -0.321* |
| | | | | | | |
| | TO Fall | 0.322* | 0.550** | 0.524** | 0.452** | 0.334* |
| | OT Fall | 0.574** | 0.583** | 0.596** | 0.587** | 0.388* |
| | OTP Fall | 0.610** | 0.599** | 0.658** | 0.668** | |
| | **ENSO Variability (Spearman Bivariate Correlation)** | | | | | |
| **Annual (ENSO)** | TO Annual | | | | | |
| | OT Annual | | | | | |
| | OTP Annual | | | | | |
| | **ENSO Variability** | | | | | |
| | TO Winter | | -0.341* | | | -0.517** |
| | OT Winter | | -0.344* | -0.364* | -0.357* | -0.482* |
| | OTP Winter | -0.432** | -0.356* | -0.319* | -0.451** | -0.344* |
| | | | | | | |
| | TO Spring | | | | | |
| | OT Spring | | | | | |
| **Seasonal (ENSO)** | OTP Spring | | | | | -0.327* |
| | | | | | | |
| | TO Summer | | | | | |
| | OT Summer | | | | | |
| | OTP Summer | | | | | |
| | | | | | | |
| | TO Fall | | | | | |
| | OT Fall | | | | | |
| | OTP Fall | | | | | |

FIGURES WITH CAPTIONS

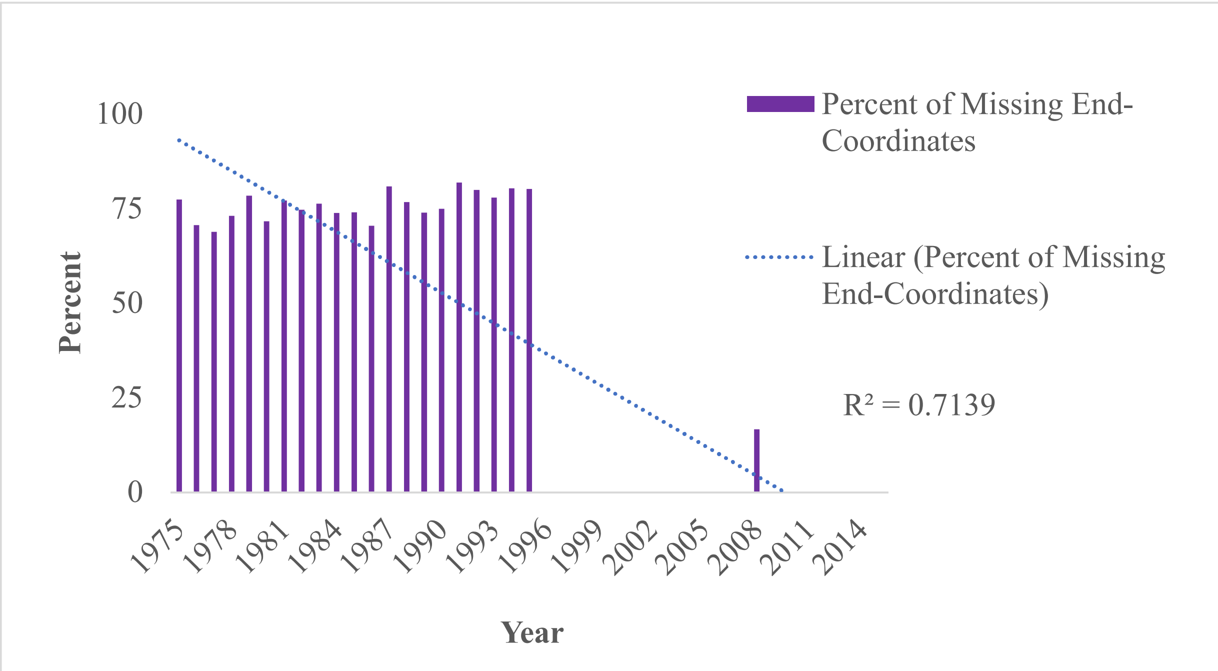


Figure 1: Annual proportion of all recorded tornadoes for which no path end-coordinates are available. In general, missing end-coordinates were relatively common during 1975-1995, and highly uncommon after 1995 (SPC 2014).

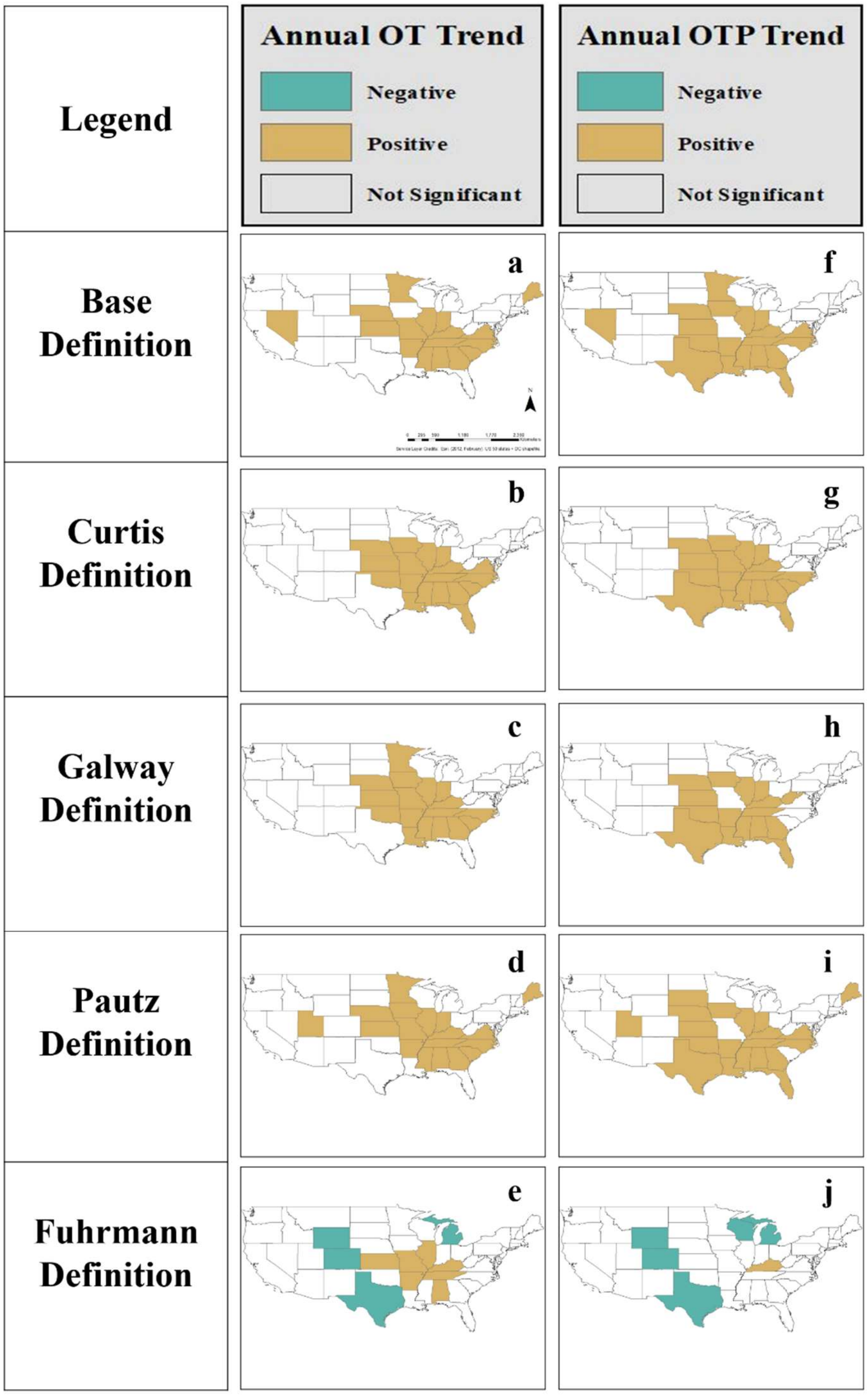


Figure 2: Significant associations (Spearman Correlation) between annual Outbreak Tornadoes (TO) and Outbreak Tornado Proportions (OTP), against time (Year).

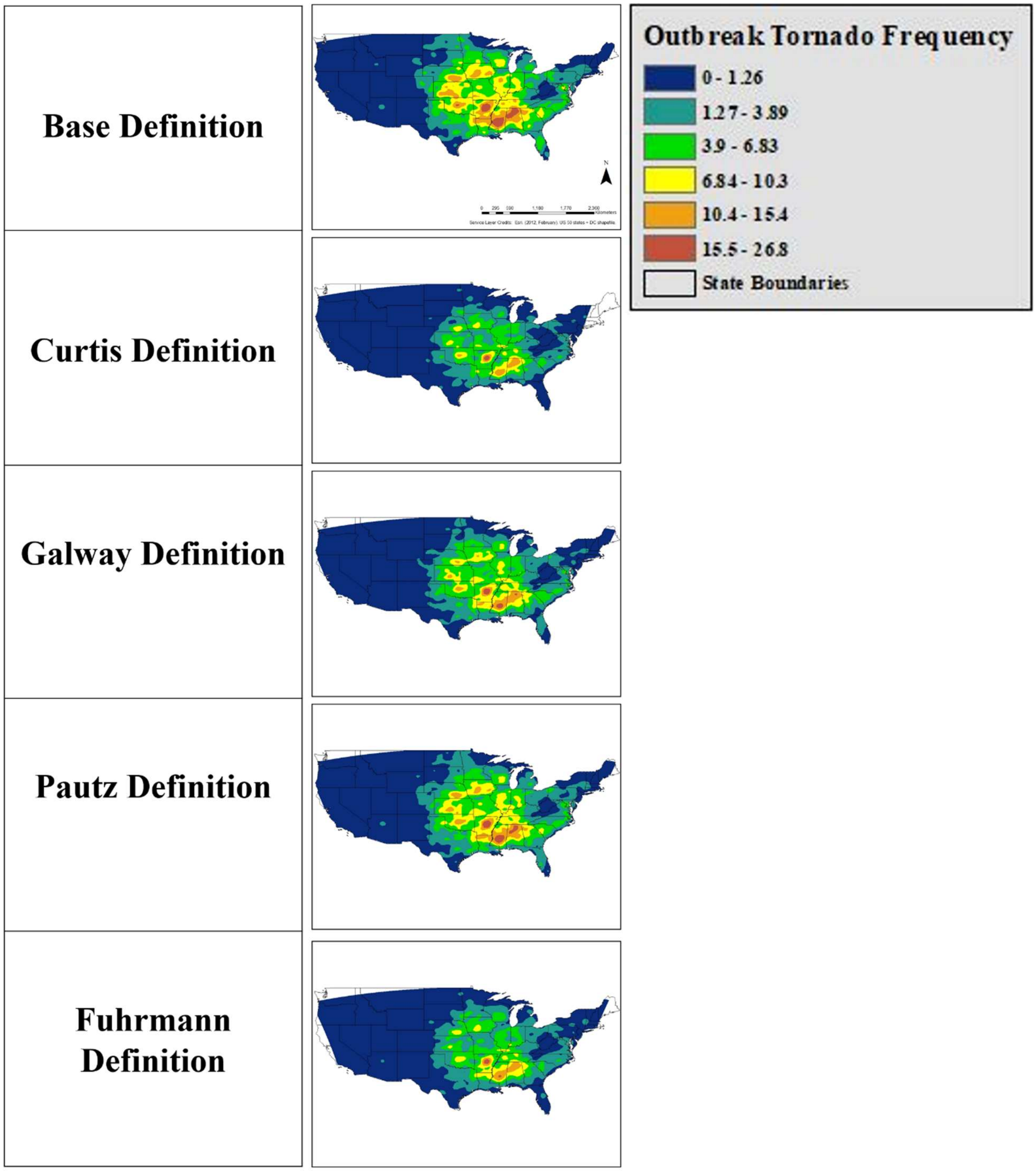


Figure 3: Outbreak Tornado frequency for the full study period, 1975-2014, for different outbreak definitions. Note that the map scale is uniform between definitions and the Natural Breaks categorization is consistent between definitions. Uniform categorization between definitions was based on the largest frequency range (in this case, the Base definition).

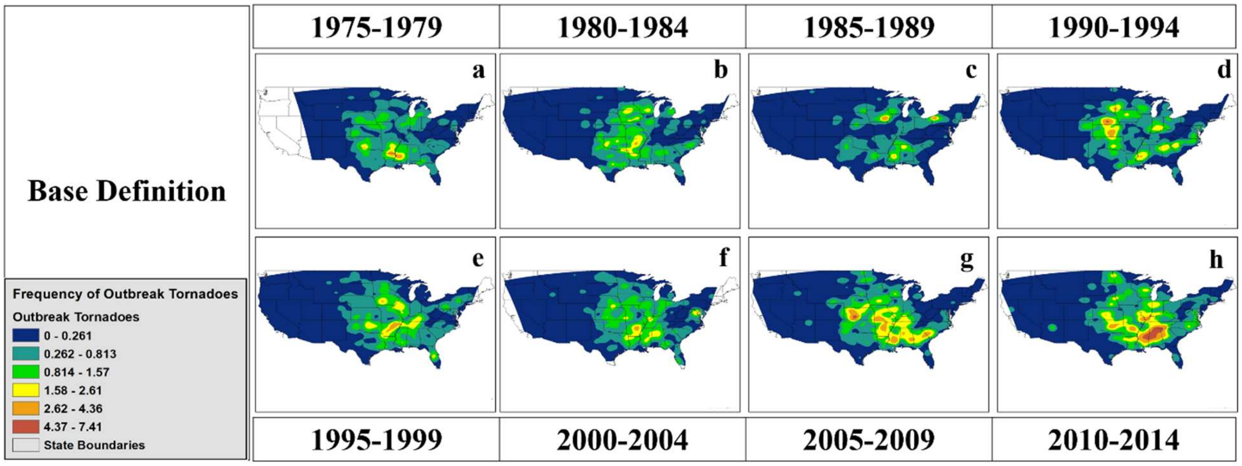


Figure 4: Outbreak Tornado (OT) frequency in 5-year increments for 1975-2014 for the Base outbreak definition.

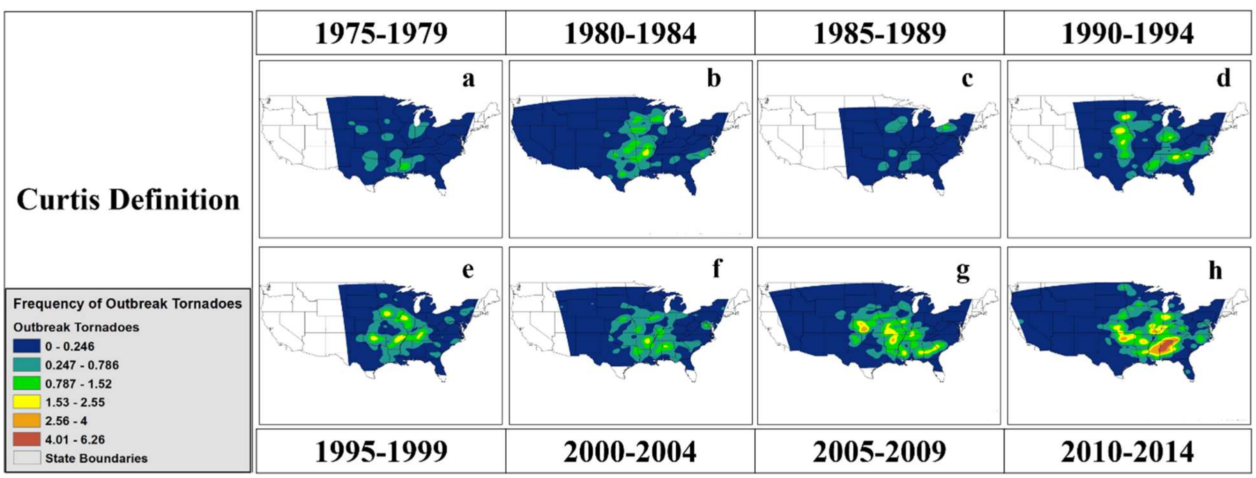


Figure 5: As in Figure 4, but for the Curtis definition.

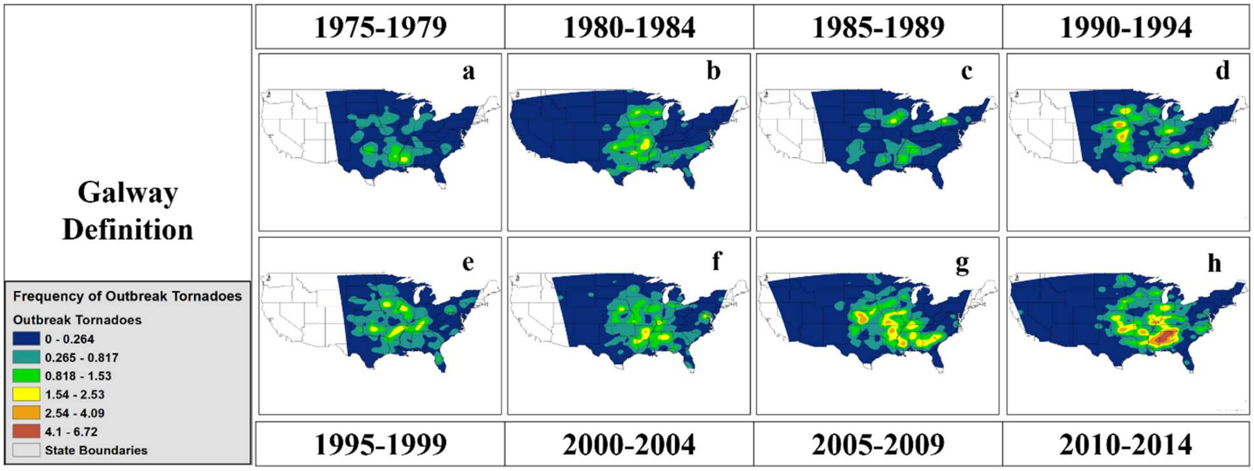


Figure 6: As in Figure 4, but for the Galway definition.

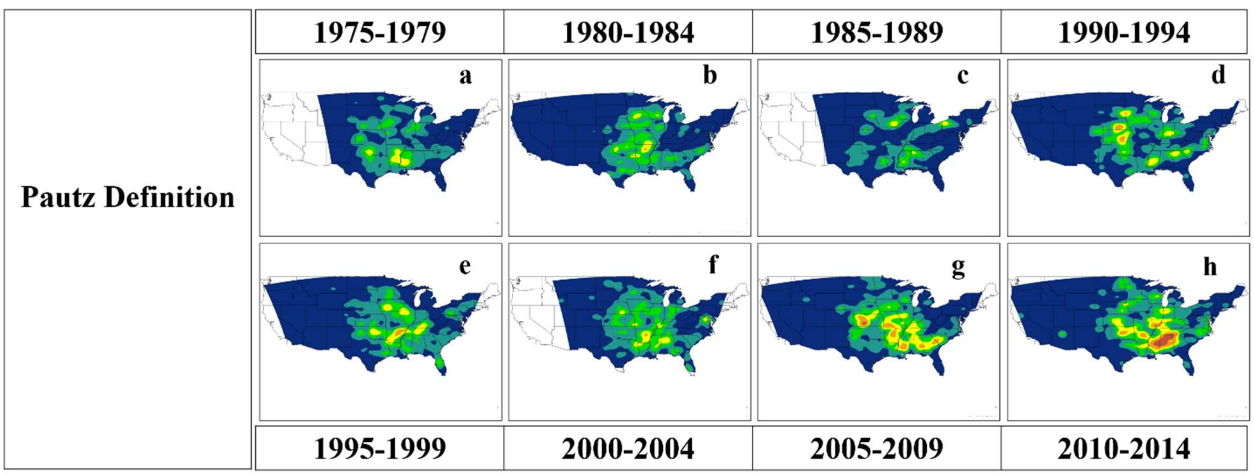


Figure 7: As in Figure 4, but for the Pautz definition.

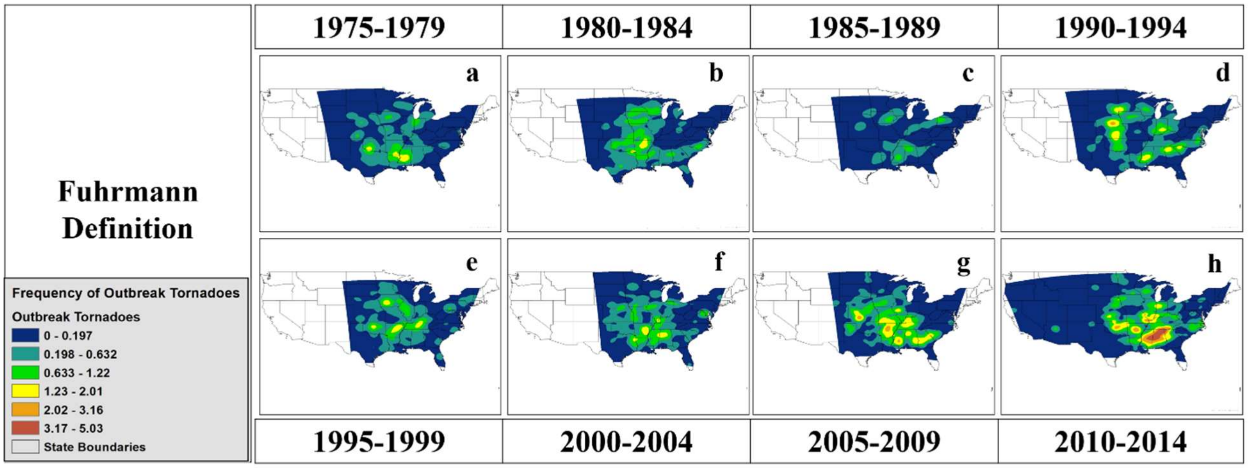


Figure 8: As in Figure 4, but for the Fuhrmann definition.


Figure 9: OT trends (Spearman Correlation against Year) by boreal astronomical season for the full study period.

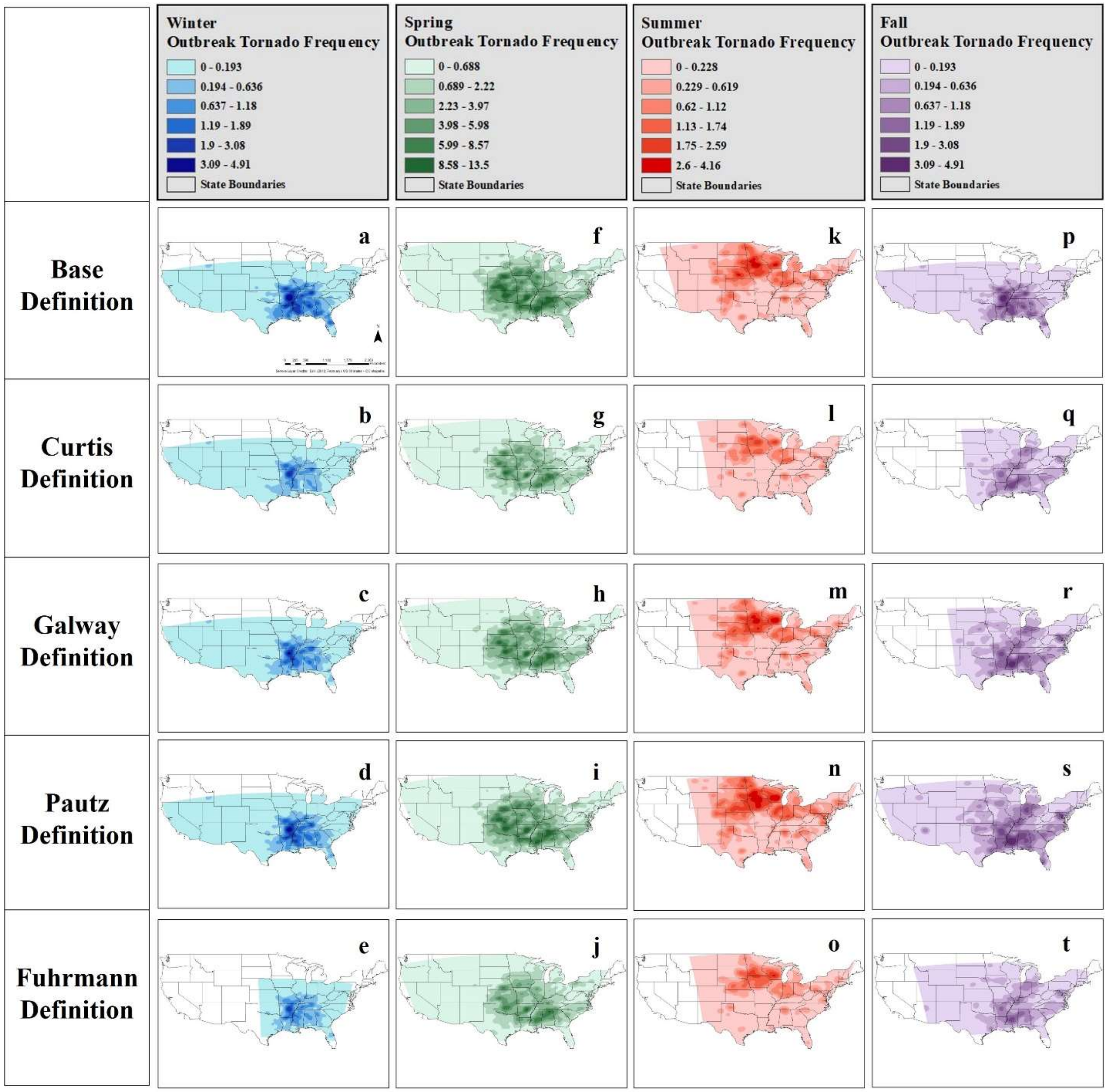


Figure 10: Outbreak Tornado (OT) frequencies by boreal astronomical season for the full study period for each definition. Note that the Natural Breaks categorization across definitions for each season is uniform. Uniform categorization is based on the definition with the largest frequency range for a given season (typically the Base definition; however, for Summer, Pautz's definition yielded the largest range).

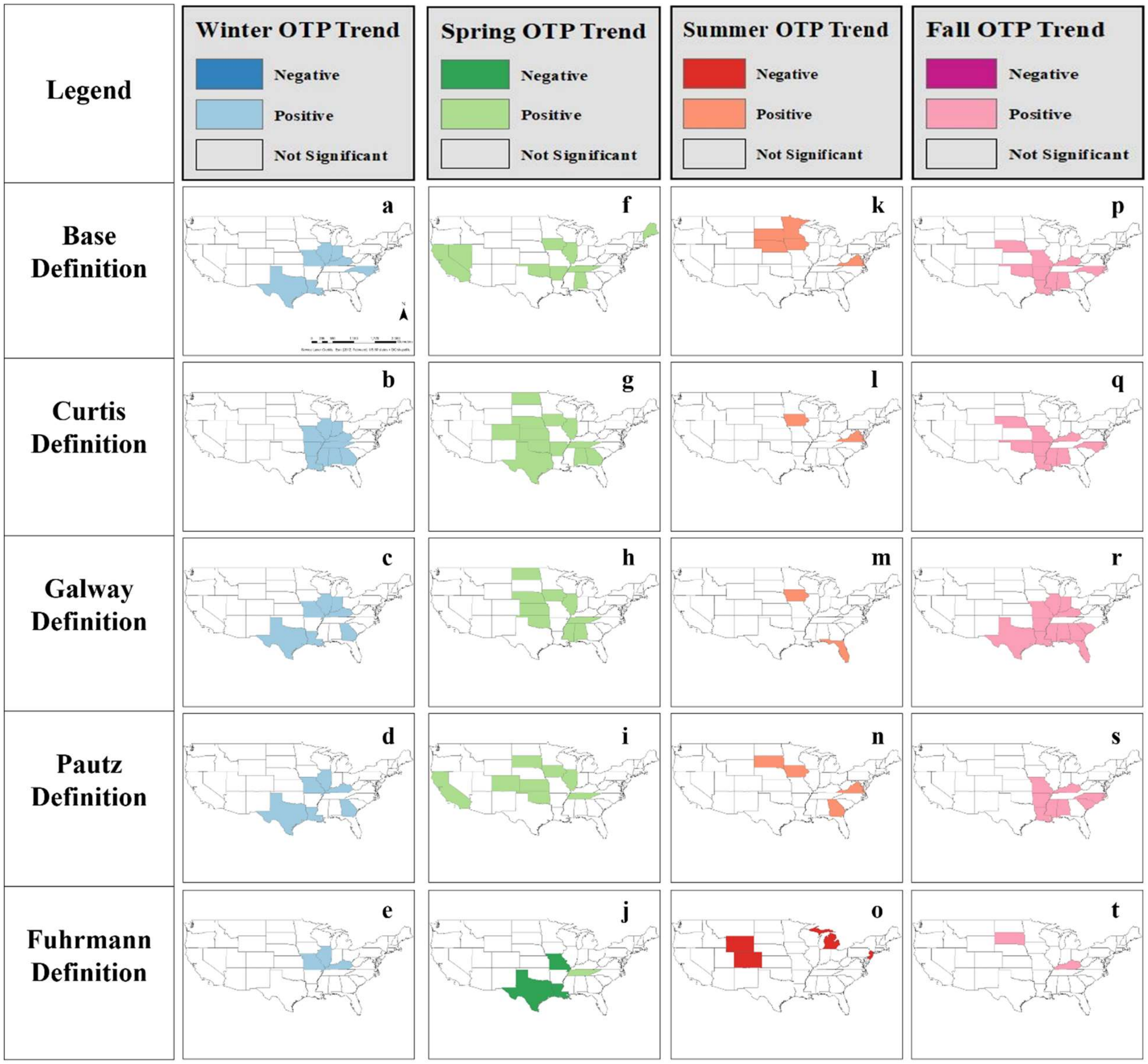


Figure 11: As in Figure 10, but for Outbreak Tornado Proportions (OTP).

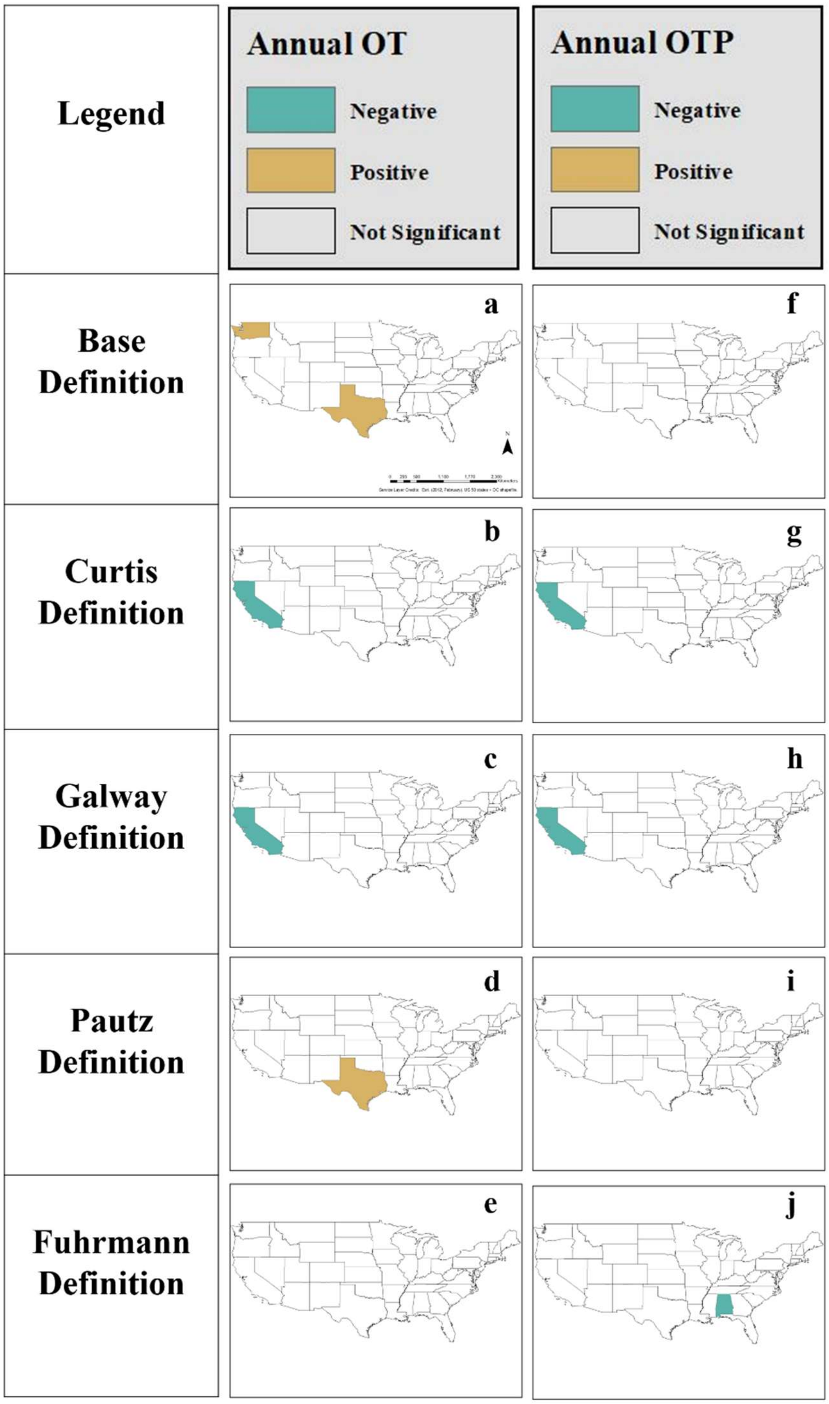


Figure 12: Significant ($p < .05$) associations (Spearman Correlation) between annual ENSO variability and annual Outbreak Tornadoes (OT) and Outbreak Tornado Proportions (OTP).


Figure 13: Significant (p < .05) associations (Spearman Correlation) between Outbreak Tornadoes (OT) and ENSO variability for each outbreak definition.


Figure 14: As in Figure 13, but for Outbreak Tornado Proportions (OTP) and ENSO variability.