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Quantifying relationships between environmental factors and accumulated tornado power on the most prolific days in the largest "outbreaks"

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ABSTRACT

An outbreak can occur as a single day or a multi-day event characterized by many tornadoes associated with specific regional scale environmental factors. The objective of this research is to quantify the relationship between environmental factors and tornado activity using big tornado days that occur in the largest multi-day groups in the United States. First, the largest groups across space and time are identified as those with at least 30 tornadoes. Then, all days with ten or more tornadoes are extracted from the largest groups. Seasonally big days in large outbreaks occur most often during April, May, and June. Accumulated tornado power (ATP) is defined as a metric of big day severity. Finally, linear mixed effect models are used to statistically examine the relationship between ATP and environmental factors including convective available potential energy and shear. Results show an upward trend in ATP at 5% per year and an increase of 124% for every 10 m/s increase in the magnitude of bulk shear. Results show an increase in ATP of 29% for every 1000 J/kg increase in CAPE. Residuals from the regression model show no regional difference. However, the number of tornadoes per unit area is larger on days when the model under-predicts ATP.

1. Introduction

Tornado outbreaks pose a risk for significant damage and casualties. Tornado outbreaks are associated with strong tornadoes and produce the vast majority of tornado-related fatalities (Elsner et al. 2014a; Fuhrmann et al. 2014; Galway 1977; Mercer et al. 2009; Schneider et al. 2004; Dean et al. 2012). In fact, three-fourths of all fatalities occur on days with the most tornadoes within a multi-day event. For example, the April 27, 2011 outbreak produced 199 tornadoes. It resulted in 316 fatalities, more than 2700 injuries, and insured losses that exceeded $11 billion (Knupp et al. 2014).

a. Tornado Climatology

Climatologies of tornadoes and outbreaks are well documented. Tornado activity is focused in an L-shaped region of the United States extending from Georgia to Oklahoma to Iowa (Concannon et al. 2000; Broyles et al. 2004). A cluster of tornadoes on a given day known as an outbreak generally occurs east of the Rocky Mountains and west of the Appalachian Mountains (Dean 2010). Tornado frequency is decreasing in the Great Plains and increasing in the Southeastern US determined by annual counts of (E)F1+ tornadoes (Gensini and Brooks 2018; Moore 2018). Tornado outbreaks are most common in the central and southeastern part of the country with the frequency of occurrence in those areas varying by season.

Tornado outbreaks occur most often during April, May, and June (Dixon et al. 2014; Galway 1977; Tippett et al. 2012, 2014; Dean 2010; Trapp 2014). In these months, the majority of outbreaks occur across the Central Plains and the Southeast. Outbreaks become less common across the Southeast and the Southern Plains during the summer months because of the northern migration of the jet stream which limits the instability fields (Concannon et al. 2000; Gensini and Ashley 2011; Jackson and Brown 2009). Outbreaks are largely confined to the Southeast during the late fall and winter months (Dean 2010). For example, November 23 - 24, 2004 was a multi-day outbreak event that extended from Texas to Florida and Georgia. It produced 95 tornadoes resulting in 42 casualties.

The diurnal distribution of tornadoes varies by location. Across the Great Plains and the Southeast, tornadoes are most common between noon and 10:00 PM (Jackson and Brown 2009). Relative to other regions, the Southeast has the greatest percentage of nighttime tornadoes (Kis and Straka 2010; Brown and McCann 2004; Gagan and Gerard 2010). The Great Plains has a peaked annual and a peaked diurnal cycle of tornado activity. In contrast, the Southeast has a considerably flatter distribution of occurrence annually and diurnally (Krocak and Brooks 2018).

b. Tornado Production

Tornadoes are produced from three primary types of storms: discrete cells (supercells), quasi-linear convective systems (QLCS), and cell clusters (Grams et al. 2012). According to researchers, 57 percent of all tornadoes occur within discrete cells, 27 percent within QLCS, and the remaining 16 percent in cell clusters (Grams et al. 2012). The convective mode producing tornadoes influences the spatial variability of tornado environments. However, supercells and linear systems specifically have minimal differences in their environmental conditions (Thompson et al. 2012). During the cold season, tornadoes are produced more frequently in QLCS in response to the frequent propagation of frontal boundaries (Trapp et al. 2005; Gallus et al. 2008; Smith et al. 2012; Cheng et al. 2016). During the warm season, the primary producers of tornadoes in highly active areas are a result of mesocyclonic storms such as supercells (Cheng et al. 2016).

It is well understood that tornadoes are not always singular events and generally occur in clusters. A tornado cluster is defined as any given grouping of tornado touchdown locations (Elsner et al. 2014a). The size and total number of tornado clusters are increasing annually (Elsner et al. 2014a). Additionally, the total number of tornadoes occurring in clusters is increasing (Elsner et al. 2014a).

The probability of a tornado on a given day rarely exceeds two percent (Brooks et al. 2003a). A tornado day is defined as any given day in which a tornado occurs. On average, there are 18 tornado days each year with eight F1 or higher tornadoes (Verbout et al. 2006). There is an annual decrease in the total number of (E)F1+ tornado days, but an increase in the number of tornado days with many tornadoes (Elsner et al. 2014a; Brooks et al. 2014; Moore 2017; Tippett et al. 2016). The frequency of tornado days is defined by a power-law distribution meaning that as the number of tornadoes on a given day increases then the number of days with that many tornadoes decreases linearly on a log-log plot (Elsner et al. 2014b; Malamud et al. 2012). Tornado days can occur consecutively with the highest probability of significant tornado occurrence in the latter half of the multi-day events (Trapp 2014).

c. Tornado Environments

This research utilizes reanalysis data from the North American Regional Reanalysis (NARR) to analyze the atmospheric environments present during tornado outbreaks across the United States. NARR is a reanalysis dataset that can be used to analyze convective environments (Gensini and Ashley 2011; Mesinger et al. 2006). An issue with the NARR data is the overestimation of favorable environments for tornadoes (Gensini and Ashley 2011). Kinematic variables are best represented by the NARR; however, thermodynamic variables are influenced by errors associated with the low-level moisture fields (Gensini et al. 2014; Allen et al. 2015). Adjusting the parcel choice is important to consider when using NARR data. A surface-based parcel is better represented in the NARR dataset because it eliminates the influence of large amounts of drying between 900 and 700 mb. (Gensini et al. 2014; Allen et al. 2015). NARR data is available in 3-hourly files and provide a more representative spatial and temporal resolution for the study of tornado outbreaks.

Tornado environments have been studied using proximity soundings and weather stations. A proximity sounding is a measure of the atmospheric variables such as temperature, pressure, and wind for a specific near-by location and relative to a time near a tornado event. Proximity soundings can pose issues when analyzing the atmospheric environments for tornadoes as a result of the temporal and spatial distribution of the soundings. The most accurate spatial and temporal "zone" for using proximity soundings to represent tornado environments is within 80 km and 2 hours of the tornado touchdown (Potvin et al. 2010). However, the minimal overlap in soundings and limited spatial distance do not provide a representative environment for larger scale phenomena such as a tornado outbreak.

Studies have identified environmental factors important to the development of tornadoes such as convective available potential energy (CAPE), wind shear, and low cloud-base heights (Brooks et al. 1994; Jackson and Brown 2009; Brown 2002; Craven et al. 2002; Dean et al. 2012; Anderson-Frey et al. 2018; Doswell and Evans 2003; Cheng et al. 2016). However, the amount of CAPE and wind shear varies by event and geographic region. It is understood that a tornado can form in low CAPE and high shear environments and high CAPE with low shear environments (Dean et al. 2012; Johns et al. 1993; Korotky et al. 1993; Brooks et al. 1994; Sherburn et al. 2016; Sherburn and Parker 2014). Low CAPE and high shear environments are common in the Southeast as a result of the ample supply of moisture coming from the Gulf of Mexico (Sherburn et al. 2016). A lifted condensation level (LCL) above 1200 m above ground level (AGL) decreases the probability of a significant tornado because low LCLs are needed to support tornado development (Rasmussen and Blanchard 1998).

Missing from these studies is a quantification of the relationship between environmental factors and collective tornado activity. Specifically, how much convective available potential energy is needed, on average, to produce a 25% increase in tornado activity? The objective of the present study is to quantify the extent to which environmental factors modulate collective tornado activity. We first identify the biggest days in the largest groups. We then determine which environmental factors best explain cumulative tornado activity. The metric of cumulative activity is accumulated tornado power and the environmental variables we consider include convective available potential energy, convective inhibition, helicity, bulk shear, and storm motion.

The paper is outlined as follows. In section 2, we describe the method we use to define tornado groups and compare the resulting list of significant large groups with previous lists of significant outbreaks. We also introduce the metric of accumulated tornado power. In section 3, we describe some of the spatial and temporal characteristics of the biggest days in the largest groups. Additionally, we quantify the relationship between ATP and the environmental variables using regression models. In section 4, we provide a summary and list the main conclusions.

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2. Data and methodology

A tornado can occur as a single isolated event or as one of several to dozens within outbreaks. The American Meteorological Society formally defines a tornado outbreak as "multiple tornado occurrences associated with a particular synoptic-scale system" (American Meteorological Society 2018). However, tornado outbreaks are also associated with certain mesoscale systems such as supercells, dry lines, and other boundaries. A tornado outbreak is generally confined to a single day; however, consecutive outbreak days result in an outbreak sequence or a multi-day event (Doswell et al. 2006). Less formally, it is commonly understood that an outbreak is a group of several to hundreds of tornadoes that occur within a relatively short time scale and over a limited geographic region (Malamud et al. 2016; Tippett et al. 2016; Elsner et al. 2014a). Tornado groups are the focus rather than individual tornadoes because groups have a larger spatial and temporal extent that is better represented with synoptic-scale environmental data (i.e. NARR) as opposed to localized environmental data from proximity soundings. We refer to them as a group rather than an outbreak since we make no attempt to associate them with a particular synoptic-scale (e.g., an extra-tropical cyclone) or mesoscale (e.g., supercell) system.

d. Grouping tornadoes

We obtain tornado data from the Storm Prediction Center's extensive tornado record (https://www.spc.noaa.gov/wcm/#data). Date, time, and location of each tornado are used to delineate groups of tornadoes. The data are subset to include only tornadoes that occur from 1994 to 2017 in the contiguous United States. The start year of 1994 marks the beginning of the extensive use of the WSR-88D radar. There are 29,372 tornadoes over this period of record.

We first project the geographic coordinates of the tornado locations using a Lambert Conic Conformal projection for the contiguous United States. The origin of the projection is situated in eastern Kansas at 39 degrees North and 96 degrees West. Then for a given tornado location i, we compute the Euclidean distance ($d_{i\,j}$) as the difference between location i and the location of tornado j. The time distance ($t_{i\,j}$) is the temporal distance between tornado i and tornado j. The space difference has units of meters and the time difference has units of seconds. We calculate the average storm motion for all big days and determine that, on average, the storms move at 15 meters per second. Therefore, the space difference is divided by 15 so the magnitude is commensurate with the corresponding time difference under the assumption that, on average, thunderstorms move at 15 meters per second. For every tornado pair, space and time differences are added to give a total space-time difference (δ_k) (Eq. 1).

$$\delta_k = d_{i\,j} + t_{i\,j}, \qquad (1)$$

where $k = n\,(n + 1)\,/\,2$ indexes each tornado pair and n is the number of tornadoes.

Next, the set of k space-time differences (δ_k) is used to place each tornado into a group. Grouping is based on proximity in space and time. If tornado i is in close proximity to tornado j based on a small value of δ_k, then the two tornadoes are considered in the same group. Grouping is done using the single-linkage method whereby the two tornadoes with the smallest δ_k are grouped together first. Then the two tornadoes (or the first tornado group and another tornado) with the next smallest δ_k are grouped second. The procedure continues by grouping tornado pairs, group-tornado pairs, and group-group pairs until there is a single large group. A group-tornado pair occurs when the shortest distance is between the closest tornado in the group and a tornado not in the group. For example, three tornadoes each 100 km apart occurring at the same time are considered a group. A fourth tornado is considered in the group if it is no more than 100 km from any one of the other three tornadoes. The grouping is done with the `hclust` function from the **stats** package in the open-source program R. It produces the same result as the ST-DBSCAN algorithm (Birant and Kut 2007).

Our interest centers on groups that are not too small (e.g., a family of tornadoes from a single supercell) and not too large (e.g., all tornadoes during a month). So we stop grouping once there are no additional pairs within a δ_k of 100K. This stopping threshold of 100K results in 3775 tornado groups with 1623 groups containing only one tornado. Also, there are 224 groups with at least 30 tornadoes (which we call "large") with the largest group having 391 tornadoes over seven days. The longest (April 25 – May 5, 2009) event within our largest groups had a duration of eleven days and produced 109 tornadoes. Roughly 72% of our large groups have a duration of two, three, or four days. There are only 6 large groups that are not multi-day events.

e. Comparison of groups with well-known outbreaks

We compare the tornado groups identified with our objective method with outbreaks that were identified using more subjective criteria. In particular, we focus the comparison on multi-day outbreaks as identified in Forbes (2006). Forbes (2006) (hereafter F06) provides a list of the top 25 outbreaks by the number of tornadoes between 1925 and 2004. Only 13 of the outbreaks identified by F06 occur after 1994; the start year of our analysis. The two lists match fairly well. We identify nine of F06's top 13 although the date ranges do not match identically. For example, the May 18–19, 1995 outbreak identified by F06 is identified by our grouping from May 12–19, 1995. F06 identifies four outbreaks over the common period covered by both studies that are not identified in our top 13 including those that occurred September 5 – 8, 2004, May 15–16, 2003, November 9–11, 2002, and April 19–20, 1996. These outbreaks show up on our list ranked by the number of tornadoes at 30, 37, 59, and 52, respectively. We identify 7 groups in our top 13 that are not mentioned in F06. We perfectly match the top tornado outbreak identified by Fuhrmann et al. (2014) using 100K. Additionally, Schneider et al. (2004) identify one of our top groups (May 3

– May 11, 2003) using a subjective clustering method.

We quantify the percent agreement between our groups and the outbreaks identified in F06 as follows. We count the total number of opportunities for a match as 13 + 13 = 26. We then subtract from this total the number of miss matches (7 + 4) and divide by the total opportunities expressing the fraction as a percentage agreement. Here the agreement is 58% [(26 − 11)/26 ∗ 100% = 58%]. By varying the stopping threshold in the clustering algorithm, we change the percent agreement. We vary the stopping threshold over the range of space-time differences from 150K to 25K in 5K intervals and find the best match with F06 in terms of percent agreement at 88% when the threshold is 50K. We use 50K as the stopping threshold for grouping tornadoes because it provides the best agreement with F06 which gives us confidence in our clustering method.

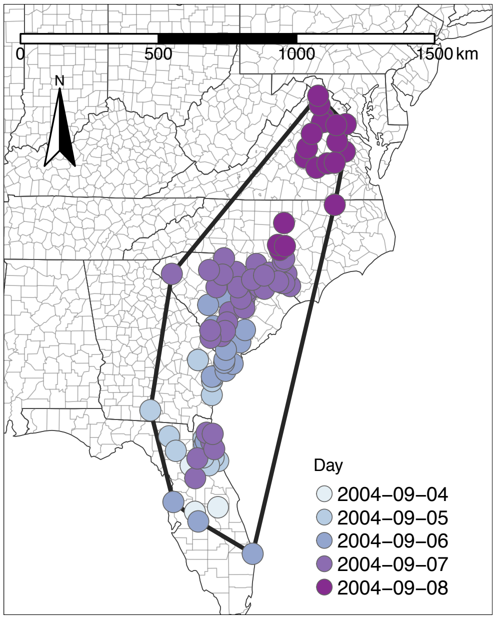

Figure 1: The September 4 – 8, 2004 event has the longest duration of all tornado groups. The black line is the hull (spatial extent) of the entire group. Each dot is colored by a different big day.

This smaller space-time difference results in 6,156 unique groups and 155 large (at least 30 tornadoes) groups. The largest group is the April 26 – April 28, 2011 event that produced 293 tornadoes. The duration of the groups ranges from 46 one-day events to one five-day event. Figure 1 shows the September 4 - 8, 2004 event which is the longest event in our large groups. Each dot is one of the 103 tornadoes in the event and is colored by the day it occurred. Multi-day events account for 69.5% of our large groups (Table 1).

Table 1: The total number of large groups and tornadoes by duration.

Duration (days)	Number of Large Groups	Number of Tornadoes
1	46	2024
2	83	4461
3	22	1620
4	3	197
5	1	103

f. Big Days in Large Groups

Our objective is to quantify the extent to which the well-known environmental factors statistically explain tornado activity at an aggregate level. Since some of the environmental factors have large diurnal fluctuations that can confound a multi-day analysis, we reduce our focus further by considering only the most prolific (big) days in these largest groups. We define the day as the 24-hour period starting at 6 AM local time (often referred to as the 'convective' day) (Doswell et al. 2006). A big convective day as part of a large group is defined as one with at least ten tornadoes.

With this definition, we find 212 big days within our large groups. Note that there is sometimes more than one big day in a single large group. Also, big days can occur within smaller groups, and our set of big days accounts for only 29% of all big days in the dataset. The top two big days (April 26, 2011, and April 27, 2011) are associated with the largest tornado group (Table 2).

We use May 30, 2004, as an example of a big day within a large group (Figure 2). The large group was identified as the eighth most prolific by our method (and the first most prolific by Forbes (2006) and extended over a two convective day period beginning on May 30th. This is the seventh biggest convective day as defined by the number of tornadoes in any large group identified. Figure 2 shows the genesis locations of the 88 tornadoes on that day with each tornado colored by the hour it occurred. The black triangle is the geographic center of the set of genesis locations (centroid), and the black polygon defines the minimum convex area encompassing all locations (convex hull) on the day.

Table 2: The top ten big days in the largest tornado groups. ATP is the accumulated tornado power on a big day.

Big Day	Number of Tornadoes	Number of Casualties	ATP (TW)
April 27, 2011	173	3069	221
April 26, 2011	104	97	46
January 21, 1999	99	171	12
June 24, 2003	94	12	3
May 5, 2007	90	24	8
May 25, 2011	90	23	9
May 30, 2004	88	46	2
May 4, 2003	86	384	31
February 5, 2008	85	482	39
April 14, 2012	84	79	32

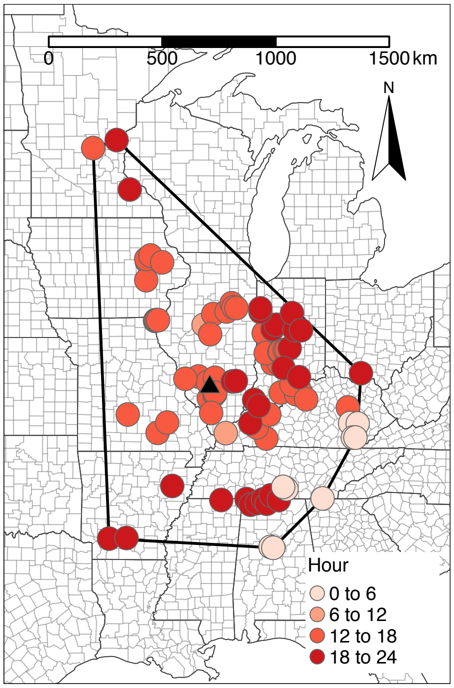

Figure 2: May 30, 2004, is a big tornado day characterized by 88 tornadoes. Each dot represents a tornado genesis location and is colored by the hour of the tornado. The black triangle is the geographic center of the genesis location. The black line defines the minimum convex polygon around the genesis locations (convex hull).

g. *Accumulated Tornado Power*

We use tornado counts to define our tornado groups because this is what other researchers have done to define outbreaks. But, our interest in this study is on the collective amount of power all the tornadoes dissipate on big days. The standard measure of tornado intensity is the Fujita and Enhanced Fujita scales (Malamud et al. 2012), but tornado path length and width are often used to compute other intensity metrics (Brooks et al. 2003b; Fuhrmann et al. 2014; Malamud et al. 2012). Over a group of tornadoes, the Destructive Potential Index (DPI) is used as a metric of the potential for damage and casualties (Thompson and Vescio 1998). Additional collective measures of intensity, such as the adjusted Fujita mile, measure the outbreak strength by using the EF scale rating times the path length of the tornado (Fuhrmann et al. 2014).

The power (P) of a tornado estimates the potential power of the wind lost at the ground. It represents the potential for destruction in units of power (watts) and is calculated using damage path area (A_p), air density (ρ), midpoint wind speed (v_j) for each EF rating ($j = 0, \cdot \cdot \cdot, J$, where J is the maximum EF rating), and the fraction of the damage path (w_j) associated with each rating (Fricker et al. 2017). P is highly correlated to DPI. However, P is useful because it is an extensive variable that can be used mathematically. Since P is an extensive variable, we sum the power for tornadoes occurring on a big day to get the accumulated tornado power (ATP). Mathematically, we express P and ATP as

$$P = A_p \rho \sum_{j=0}^{J} w_j v_j \tag{2a}$$

$$ATP = \sum_{i=1}^{n} P_i \,, \tag{2b}$$

where n is the number of tornadoes occurring in the big day.

In 1994, the tornado record changed the measurement of the path width from an average width over the entire tornado track to the maximum width experienced during the tornado.

Our record starts in 1994 and is not impacted by this change in reporting. ATP is calculated using maximum path width and the maximum EF rating of each tornado on the big day. Therefore, ATP is considered a maximum representation of tornado power on a given day.

h. Environmental Factors

Given a big day with at least ten tornadoes, we quantify the effect of known environmental factors on accumulated tornado power (ATP). We obtain the National Center for Environmental Prediction's (NCEP) North American Regional Reanalysis (NARR) from the National Center for Atmospheric Research (NCAR) (National Centers for Environmental Prediction). We use the original NCEP NARR 3-hourly files. These files contain environmental data for each day ranging from 0Z to 21Z in 3-hour increments. For each big day, we calculate the closest 3-hour time prior to the first tornado in each big day (Table 3). We pick a time before the event starts because we want to sample the pre-storm environment for each big day. We use only the big days that occur between January 1994 and December 2017 resulting in a total of 212 big days.

Each NARR file has 434 atmospheric variables. We consider several of them representing instability and wind shear including the 180 to 0 mb above ground level (AGL) CAPE and CIN (layer 375, 376), the 0 to 3000 m AGL helicity (layer 323), and the 0 to 6000 m AGL U and V components of storm motion (layer 324, 325). Additionally, we download the U and V components of wind for the 1000 mb (layer 260, 261) and 500 mb (layer 117, 118) levels. We compute total storm motion as the square root of the sum of the velocity components squared. We compute the bulk shear as the square root of the sum of the squared differences between the U and V winds for the 1000 mb and 500 mb levels. We use these variables because they are known to be associated with tornado development (Brooks et al. 1994; Jackson and Brown 2009; Brown 2002; Craven et al. 2002; Dean et al. 2012; Anderson-Frey et al. 2018; Doswell and Evans 2003; Cheng et al. 2016).

Table 3: Total number of big days associated with each Z time.

Zulu Time	**Number of Big Days**
00Z	3
03Z	0
06Z	0
09Z	53
12Z	38
15Z	56
18Z	50
21Z	12

Table 4: The maximum and minimum values associated with each big day. The top 3 rows represent the top three big days sorted by ATP. The bottom three rows are the bottom 3 big days by ATP.

Big Day	**Maximum CAPE (J/kg)**	**Minimum CIN (J/kg)**	**Maximum Helicity (m^2/s^2)**	**Maximum Bulk Shear (m/s)**	**ATP (TW)**
Top 3 Big Days					
April 27, 2011	1720	-262	935	35	220
April 24, 2010	2740	-196	482	43	64
April 26, 2011	3540	-299	313	34	46
Bottom 3 Big Days					
May 18, 2000	2530	-135	388	27	0.04
April 25, 2003	1100	-206	488	18	0.04
September 26, 2004	920	-138	315	18	0.01

Values for each NARR variable on each big day are available as a 277 by 349 rectangular raster. The corresponding big day convex hull is used as a mask, and the raster values falling under the mask are composited into a single number. For the variables CAPE, bulk shear, and helicity, the composite consists of taking the minimum value. In this way, every big day value of ATP is associated with each of the environmental variables representing a spatial composite of the regional scale environment in which the tornadoes occurred (Table 4). The maximum and minimum values provide a better representation of the environmental conditions on each big day because they eliminate the influence of contamination by small scale features such as cold pools and averaging small and large values of each variable. Said another way, the maximum (or minimum) is chosen for the composite value to ensure the variable is a sample from only the unstable airmass.

3. Results

a. Big Day Climatology

For each big day in a large group, we calculate the centroid from the tornado genesis locations. Figure 3 shows the centroids of all 212 big days in large tornado groups with the size and color of the triangle scaled by the number of tornadoes in the group. Most of the big days occur east of Rockies and west of the Appalachians. In particular, there is a cluster of centroids across the middle South extending northwestward toward the central Great Plains. There is a tendency for the biggest days to occur farther east.

A convex hull is obtained for each big day. The convex hull represents the spatial domain of tornado activity on that day. Counties within the hull define the political extent of the activity, and we tally the number of times each county falls within (including partially) a big day hull (Figure 4). Of course, larger counties will have a higher count considering all else being equal, but a pattern emerges highlighting the counties over the middle South. Counties affected most often by big days in large groups include those of southern Missouri and northern Arkansas into western Kentucky and western Tennessee.

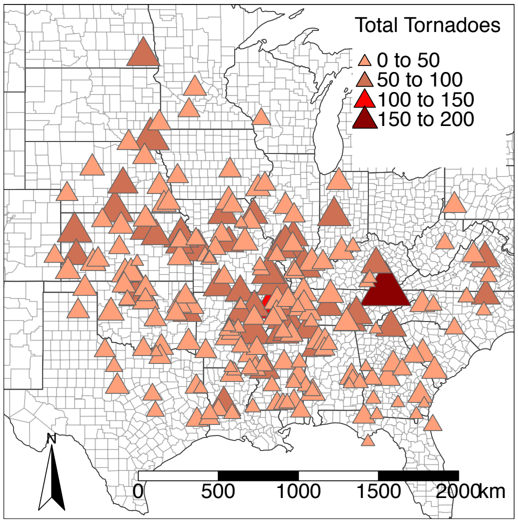

Figure 3: Centroids of genesis locations occurring on big days in large groups. The triangles are sized and colored by the number of tornadoes on that day.

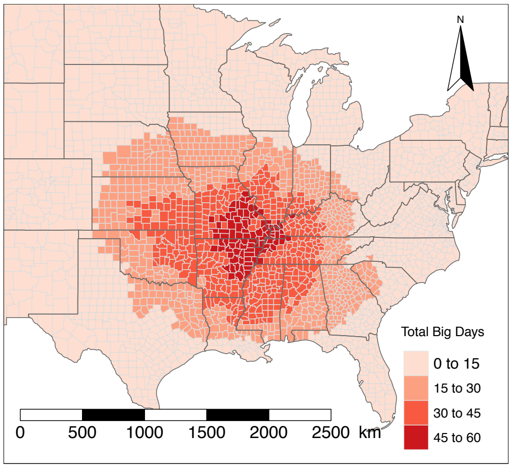

Figure 4: Big day density by county.

b. Accumulated Tornado Power

Table 2 identifies the ATP for the top 10 big days in the largest groups. It includes the infamous days of April 27, 2011, and May 4, 2003. ATP on April 27, 2011, is nearly four times the ATP on the next most powerful day, April 26, 2011. For big days, the Spearman rank correlation between ATP and the number of tornadoes is 0.63 indicating a strong relationship.

Big days within large groups are most likely to occur during April through June with some months also showing a secondary peak after summer. Monthly average ATP peaks in April followed by March and May (Table 5). Average

ATP is similar between November and May. While fewer in number, big days in large groups during November tend to produce stronger tornadoes leading to higher values of ATP.

Table 5: Seasonal variation in ATP (TW), number of tornadoes, and the number of big days by month. The number of tornadoes and the number of big days is based on the period 1994 – 2017.

Month	**Average ATP (TW)**	**Number of Tornadoes**	**Number of Big Days**
January	4.72	416	11
February	7.20	333	10
March	12.60	444	11
April	13.10	2022	50
May	8.32	2473	56
June	3.42	897	23
July	0.63	43	2
August	1.47	72	2
September	1.01	460	16
October	2.61	303	9
November	8.11	590	14
December	4.76	191	8

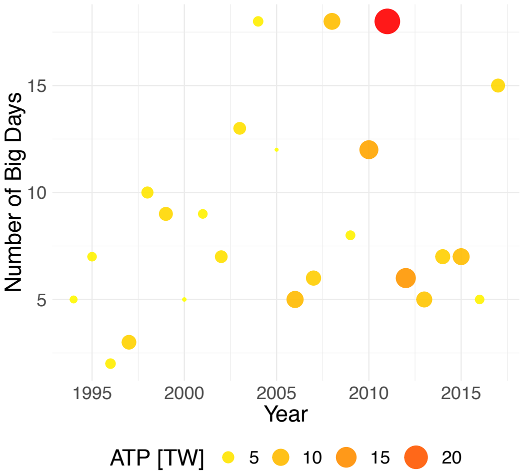

Figure 5: Number of big days by year, 1994 – 2017. Points are sized and colored by annual average ATP.

Figure 5 shows the time series of the annual number of big days in large groups and the annual average ATP over those days. The inter-annual variation in the number of big days is quite large ranging between 2 and 18. However, there is no long-term trend in the number of big days annually. On the other hand, the annual average ATP appears to be increasing with the higher values occurring later in the period which is consistent with the findings of Elsner et al. 2019.

c. *Quantifying the Relationship Between ATP and Environmental Factors*

With our sample of 212 big days from 1994 to 2017, we use a linear mixed effects model to quantify the relationship between ATP and regional scale environmental factors. This type of model allows us to quantify, for example, the effect of CAPE on ATP while controlling for the time of year. These models are considered mixed effects because the inputs are both fixed and random effects. A fixed effect is an explanatory variable (x) used to predict and quantify the relationship to our response variable. The fixed effects in this model are the environmental variables and year of the big days. The year is included as a fixed effect because we see that ATP is increasing over time and we do not want this to confound the other fixed effects (Figure 5). We treat month as a random intercept effect because of the large seasonality in ATP (Table 5). The coefficient (β_{Year}) is the annual trend in ATP.

The values of ATP are right skewed with most big days having smaller values less than 5 TW. However, 23% of our big days have an ATP value greater than 10 TW. The top day has more than 220 TW ATP (see Table 2). Because the data are not normally distributed, ATP is transformed to the log scale. The distribution of ATP on a log scale is nearly normally distributed about the mean value of 0.86 TW. The median value of the distribution is 1.2 TW. Therefore, the model uses the logarithm of ATP as the response variable.

We examine various combinations of our fixed effects and find that the best model for the logarithm of ATP for each outbreak day (i) is

$$\begin{aligned}\log(\text{ATP}_i) = {} & \beta_0 + \beta_{\text{Year}}\text{Year}_i + \beta_{\text{CAPE}}\text{CAPE}_i \\ & + \beta_{\text{Shear}}\text{Shear}_i + \beta_{\text{Helicity}}\text{Helicity}_i \\ & + \beta_{\text{CIN}}\text{CIN}_i + \boldsymbol{\beta}_{\text{Month}}\,(1|\text{Month}_i) \\ & + \varepsilon_i\,, \qquad (3)\end{aligned}$$

where the coefficients Year, CAPE, Shear, Helicity, CIN, and Month are given by the corresponding β's. Month is a random effect so $\boldsymbol{\beta}_{\text{Month}}$ is a vector of coefficients.

The above model is best in the sense that it has the lowest Akaike Information Criterion (AIC) score which is used in model selection and measures the overall quality of the model. The correlation between ATP and model predicted ATP is 0.33. Storm motion and bulk shear are strongly correlated (0.59) so storm motion is not included in the model.

Table 6: Coefficient estimates from a regression model of ATP onto year, CAPE, bulk shear, CIN, and helicity using data from n = 212 big days in large groups over the period. The standard error is on the estimate and its *t* value is the ratio of the estimate to the standard error. The coefficients were determined via an interactive maximum likelihood approach with the `lmer` function from the **lme4** package for R (Bates et al. 2015)

Predictor	**Coefficient Estimate**	**Standard Error**	***t* value**
Intercept	25.032	0.532	47.060
Year	0.050	0.016	3.023
CAPE	0.258	0.095	2.708
Bulk Shear	0.807	0.169	4.786
Helicity	0.153	0.061	2.506
CIN	-0.098	0.083	-1.179

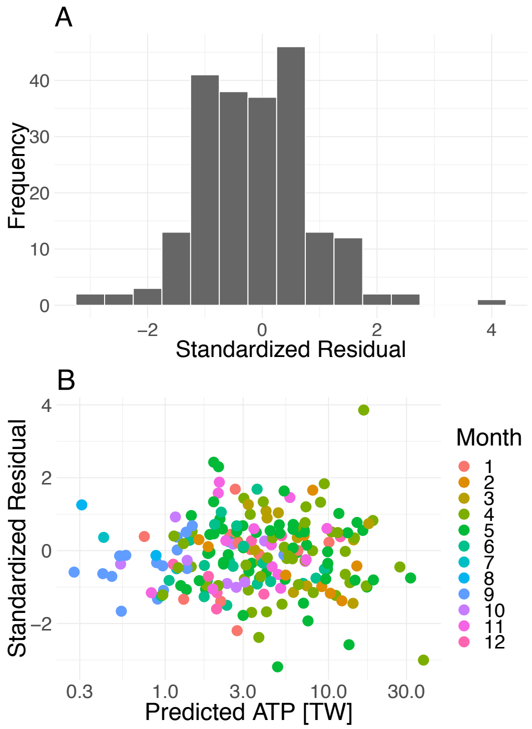

Figure 6: Conditional standardized residuals from the linear regression model. (A) Histogram and (B) Residuals as a function of predicted values of ATP.

Model coefficients are given in Table 6. We interpret them as follows. The coefficient on the year term (β_{Year}) indicates an upward trend in per big-day outbreak ATP amounting to 5% [(2%, 8%), 95% uncertainty interval (UI)] per annum. Note that the percent increase is calculated using $(e^{\beta_{\text{Year}}} - 1) * 100\%$. The coefficient on the CAPE (β_{CAPE}) term indicates that for every 1000 J/kg increase in CAPE, ATP increases by 29 % [(7%, 44%), 95% uncertainty interval (UI)] holding the other variables constant. The coefficient on the bulk shear term (β_{Shear}) indicates that for every 10 m/s increase in the magnitude of bulk shear, ATP increases by 124% holding the other variables constant. ATP increases by 17% for every 100 m^2/s^2 increase in helicity when the other variables are held constant. Additionally, the coefficient of CIN (β_{CIN}) indicates a 9% decrease in ATP for every 100 J/kg increase in CIN holding the other variables constant.

We compute the conditional standardized residuals (Santos Nobre and da Motta Singer 2007) between the actual and predicted values of ATP (Figure 6). The histogram of the residuals can be described by a normal distribution, and a plot of the residuals as a function of the predicted values by month shows no apparent pattern indicative of an adequate model.

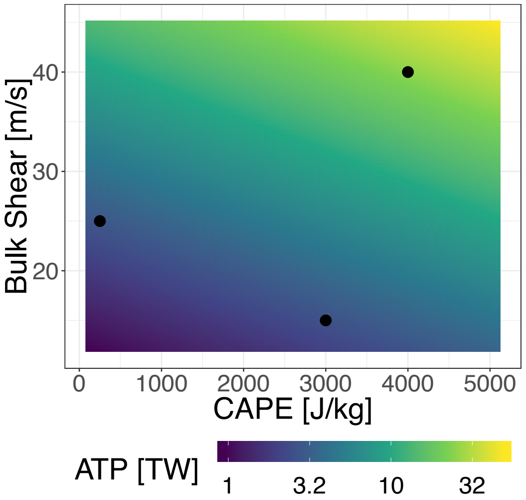

Figure 7: Predictions of ATP across a range of CAPE and bulk shear values holding CIN, helicity, year, and month as constants.

We use the model to predict ATP across a range of CAPE and bulk shear values while setting CIN and helicity to their mean values (-200 J/kg and 40 m^2/s^2 respectively), year to 2017 and month to April (Figure 7). Year is assigned to 2017 because it is the last year in our dataset and month is assigned to April because that is the peak month for tornado activity and ATP. We see that ATP increases with increasing values of both CAPE and bulk shear. For values of CAPE at 250 J/kg and Shear of 25 m/s, the model estimates an average ATP of 2.82 TW. Similarly, there is an average ATP of 2.56 TW when CAPE is 3000 J/kg with a Shear value of 15 m/s. For values of CAPE equal to 4000 J/kg and a Shear value of 40 m/s, the model estimates an average ATP of 24.93 TW.

Figure 8 shows the actual ATP versus the predicted ATP for the 212 big tornado days. Lighter blue points, which tend to cluster toward greater ATP, indicate more tornado casualties (death plus direct injuries). Increases in CAPE and bulk shear lead to stronger tornadoes with increased potential for casualties. The points tend to fall along a line from lower left to upper right but with a slope less than one.

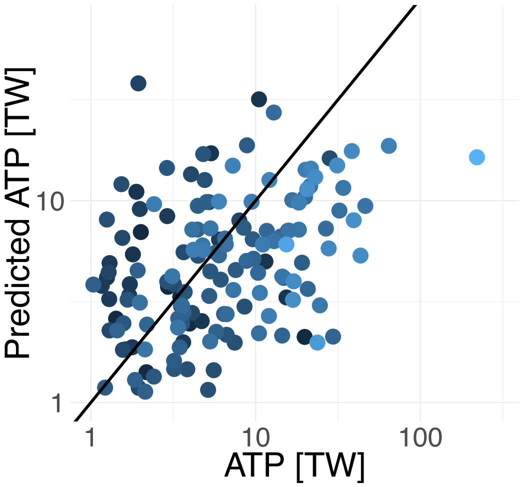

Figure 8: Actual versus predicted accumulated tornado power (ATP) for the n = 212 big tornado days. The predicted are based on the regression model (Eq. 3). The color shading from dark to light indicates an increasing number of casualties.

Big days with more ATP than predicted by the model are the points that fall to the right of the diagonal line. We note that April 27, 2011, and April 26, 2011, are examples of days more energetic than predicted by the model, and April 19, 2011, and February 20, 2014, are examples of days less energetic than predicted by the model. We analyze the spatial distribution of the most over- and under-predicted ATP on big days. We see no geographic preference for big days that are under-predicted compared with big days that are over-predicted. Further, we see no distinction in the size of the areas.

On the other hand, the average number of tornadoes per unit area on the subset of the big days that are most under-predicted is 2.3 per square kilometer compared to 1.6 per square meter on the subset of the big days that are most over-predicted. The average area of the under-predicted days is 52.8 square kilometers relative to 37.0 square kilometers for over-predicted days. This implies that the model might be improved by including environmental factors that explain the efficiency of tornado production. More research on this is needed.

Table 7: The most over- and under-predicted big days. The actual ATP was calculated and the predicted is determined by the output of the regression model.

Big Day	**Actual ATP (TW)**	**Predicted ATP (TW)**
Over Predicted		
April 24, 2003	1.25	8.06
April 19, 2011	1.94	38.13
February 20, 2014	1.53	12.07
April 3, 2017	1.89	11.06
Under Predicted		
May 3, 1999	23.7	1.98
May 22, 2004	29.5	2.12
November 23, 2004	14.5	2.15
April 26, 2011	46.3	9.4
April 27, 2011	220.9	16.4

4. Summary and List of Major Findings

April 27, 2011, was the biggest day in the largest, costliest, and one of the deadliest tornado outbreaks ever recorded in the United States (Knox et al. 2013). The multi-day event affected 21 states from Texas to New York. In this study, we first identify all big days over the period 1994 – 2017 having ten or more tornadoes that occur in multi-day groups having 30 or more tornadoes (large groups). This is done with a clustering technique on the set of space-time differences between all tornadoes. Then, for each big day, we compute the accumulated tornado power (ATP) as the sum total power for all tornadoes on that day. Next, we use reanalysis grids to identify the extremes in CAPE, CIN, bulk shear, and helicity over the domain defined by the tornado locations on these big days. A regression model is used to quantify the relationship between ATP and four well-accepted environmental factors. We find an upward trend in ATP at the rate of 5% per annum. We also find that ATP increases significantly with additional CAPE, CIN, helicity and bulk shear. Finally, residuals are analyzed to diagnose model adequacy and to identify the largest under and over predictions.

The major findings are:

- An objective cluster technique can reliably identify tornado outbreaks
- Accumulated tornado power (ATP) is a useful metric of outbreak severity.
- ATP is increasing by 5% each year on average.
- As CAPE increases by 1000 J/kg, ATP increases by 29% on average.
- ATP increases by 124% for every 10 m/s increase in bulk shear on average.
- ATP increases by 17% for every 100 m^2/s^2 increase in helicity on average.
- For every 100 J/kg increase in CIN, ATP increases by 9% on average.

The study is limited by sample size (only 212 big day cases in large groups) and by an exclusive focus on the last 20 years of a much longer tornado record. The study can be improved by considering more cases from the earlier years. The cost of including earlier data would be greater uncertainty on the estimates of per-tornado power. The study might also be improved by including other environmental factors in the model, especially ones that are related to the efficiency of tornado production. Future work will examine the spatial variation in the factors affecting outbreak severity and quantify the relationship between outbreak casualties and the environmental factors controlling for how many people were within the outbreak area.

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The code used to produce the results of this paper is available at https://github.com/jelsner/tor-clusters

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REVIEWER COMMENTS

Editor: Roger Edwards:

This is a very interesting topic, with some unexplored territory and potential in terms of the ATE concept and comparative analysis across tornado-outbreak events. We were able to recruit three highly qualified reviewers who were quite thorough and thoughtful in offering beneficial insights for improvement. Unfortunately, based on the collective input from the reviewers, it appears the needed changes are too deep and broad in nature to keep the paper in the review process. **We are declining the submission at this time**.

I strongly encourage you to fortify this research with respect to all of the comments of the reviewers, then after doing so, resubmit your manuscript to EJSSM or any topical journal in the future. Obviously I would prefer for you to resubmit here and revise as advised by me and these reviewers, since you're likely to get similar review input from reviewers at other severe-storms-familiar journals, and also, you'll have cleared what's likely the biggest hurdles having this work in its most robust, publishable form. If in resubmission, you can provide adequate responses to all the current reviewers' concerns for the editor's sake, that would be a great step, since a new submission might include one, two or all three new reviewers anyway. We could avoid having to revisit old ground in the revision process.

I won't regurgitate the bulk of the reviews here, as they are attached, but among many major concerns for me and the reviewers were:

1) The (un?)representativeness of the 18Z sampling methodology, a unanimous major issue of all 3 reviewers (and rightly so), including failure to account for the diversity of regimes that can produce tornadoes within any given single "outbreak day" (Reviewer A/Frame had some excellent and insightful commentary here),

We adjusted our sampling method. We want to sample the pre-storm environment in this research. As a result, we now use the nearest 3-hour Z time prior to first tornado on the big day. Using the pre-storm environment, we get a more representative sample of the environment generating these tornadoes.

2) What appears to be a very loose, highly unconventional and temporally overly broad umbrella for an outbreak, with inadequate justification,

Our research analyzes big days (10+ tornadoes) in large groups (30+ tornadoes). We do not refer to these as outbreaks because we do not link them to synoptic systems or reference storm types. We explained our clustering technique in greater detail as well as the characteristics of our multi-day events. We picked 30 or more tornadoes to define our big groups because our longest event is 5 days using the 50K cluster threshold. Similar to one of Reviewer C's comments, that would average to 6 tornadoes a day. That multi-day event specifically produced many more tornadoes than 30 (Figure 1). However, large groups are not our focus and simply a way for us to extract big days that are associated with well-known large multi-day groups.

3) An unsupported claim of utility for ATE (or as Reviewer B put it: "Regarding the findings, I would like to challenge the second: ATE is useful. How is it useful?" and finally,

We changed the acronym of ATE because it is not in units of energy. Instead, it is in units of power. Therefore, accumulated tornado energy is now accumulated tornado power (ATP). ATP's utility stems from the fact that it is an extensive variable. An outbreak with an ATP of 100 GW has twice the power of an outbreak with an ATP of 50 GW. Fricker et al. (2017) use energy dissipation which has units of power. This is not true of variables like DPI, etc.

4) The apparent calculation of storm motion but advertised as shear, per Reviewer A, which indicates to me either a fundamental misunderstanding or lack of carefulness regarding a crucial ingredient in the recipe for the analysis.

The calculation of bulk shear was corrected.

Between all three reviews, the volume and scope of needed changes is rather massive -- beyond what I normally would frame as "major" revision. While this may seem like bad news, I believe your work can be revised to not only publishable form, but potentially highly impactful contribution to the tornado climatology literature, if you take great care to address the
reviewers' concerns and suggestions.

Please do not be discouraged. Your manuscript's focus and subject matter suit the journal well, and again, there is really good potential in what you are doing. If you have any questions or concerns, please let me know; otherwise I look forward to a resubmission when you are ready.

Reviewer A: Jeffrey Frame

Recommendation: Rejection

General Comments:

This manuscript identifies the most prolific tornado day of multi-day outbreaks and then ties them to changes in severe parameters such as CAPE and vertical wind shear. While the results of the clustering methodology are interesting and show promise, serious flaws in the methods employed to diagnose the environmental parameters, in my opinion, prevent the manuscript from being published in its current form. My concerns are summarized in greater detail below. While it is possible for the authors to significantly revise this methodology, it falls beyond the usual scope of major revisions. It is also possible that the authors remove all content related to environmental parameters completely, leaving little novel scientific content in the manuscript. I thus recommend rejection.

Substantive Comments:

1. Environments that produce tornado outbreaks are often meteorologically complex, and usually exhibit substantial variability in both space and time. The method employed herein, however, characterizes such environments by a single maximum value of CAPE, bulk shear, and storm-relative helicity and a single minimum value of CIN, taken at a single time (1800 UTC). There are several serious scientific problems with this methodology. First, no check is made as to how representative these maximum values are of the large-scale environment in which the tornadoes occurred, as CAPE and shear can vary by as much as factors of three or four or more across a tornado outbreak area throughout the several-hour period of an outbreak. The CAPE and shear maxima can also be offset by hundreds or even over a thousand kilometers, and no check was made to ensure that the environments were actually characterized by the superpositioning of the CAPE and shear values obtained from the maxima. Such a check is important given the sometimes large geographic domains depicted in Fig. 10. For example, in the case of a strong extratropical cyclone-driven tornado outbreak, the maximum in shear and helicity is generally farther north, closer to the surface cyclone, possibly in a regime of more limited buoyancy, while the CAPE maximum could be significantly farther south. The methodology employed thus results in large geographic areas being described by a combination of parameters that may have not ever existed contemporaneously in reality.

The maximum values of the environmental variables are representative of the pre-outbreak environment. We have adjusted the methodology to get the NARR files for the closest 3-hour Z time prior to the occurrence of the first tornado in the outbreak and over the region defined by the set of all tornadoes in the big day. This is done for each big day.

Furthermore, severe storm environments can rapidly vary in time. The selection of a single time (1800 UTC) to characterize the evolution of a tornado outbreak that may have occurred over a several-hour period is troublesome and may have limited the interpretation of the results. For example, in a strong extratropical cyclone-driven tornado outbreak, the maximum in storm-relative helicity (SRH) generally exists north of the synoptic warm front, in a regime typified by strong geostrophic warm-air advection and thus veering winds with height and likely substantial clockwise hodograph curvature. The frontal inversion north of the warm front, while usually preventing the existence of substantial (or sometimes any) positive buoyancy also limits vertical mixing, allowing values of high shear to persist. This area could have then experienced one or more tornadoes during the outbreak following the passage of the synoptic warm front, after which CAPE would presumably be present. Similarly, the analysis could be contaminated by convective cold pools at 1800 UTC that are not reflective of the tornadic environments. Additionally, the methodology outlined in the paper does not prevent, for example, a high value of SRH co-located with zero CAPE to represent the SRH of the entire unstable warm sector. Given that at least some of the SRH values used in the analysis could have been co-located with zero (or near zero) CAPE at 1800 UTC, this may explain the somewhat surprising lack of a signal of more violent tornadoes with stronger SRH discussed in the manuscript.

We want to sample the pre-outbreak environment on each of the big tornado days. Therefore, our Z-times have changed and vary by big day. We choose the nearest 3-hour Z time that occurs prior to the first tornado touchdown on each big day. You can see how many big days fall in each Z-time category in Table 3.

Table 3: Total number of big days associated with each Z time.

Zulu Time	*Number of Big Days*
00Z	*3*
03Z	*0*
06Z	*0*
09Z	*53*
12Z	*38*
15Z	*56*
18Z	*50*
21Z	*12*

The CAPE and shear values extracted are those within the domain defined by the set of tornadoes occurring on each big day. So, the maximum value extracted for each variable is contained within the bounds of the big day. The maximum value is chosen because CAPE and shear values can differ throughout the area of the big day and to remove the influence of averaging variables as these variables could be impacted by other local or meso-scale features.

2. The diurnal peak in tornadoes is between 2pm and 8pm in most regions of the United States, not “in the early afternoon” as stated in the first paragraph of section 2e. Thus, a choice of 2100 or 0000 UTC would have likely been more appropriate for a single analysis time, but I strongly believe that a more detailed time filtering of the NARR analyses that considered the times when the tornadoes actually occurred should be employed.

We are interested in the environment prior to the outbreak. We now use the closest 3-hour Z time to the start of the big day as defined by the first tornado in the outbreak.

3. In the second paragraph of section 2e, it is stated that bulk vertical wind shear was computed by summing the squares of the zonal and meridional components of storm motion and then taking the square root. This calculation, however, yields the storm motion, not the bulk wind shear. Surface to 500 mb bulk wind shear (a decent proxy for 0-6 km bulk shear) can be computed from the NARR data by subtracting the surface u and v components of the wind from the 500 mb u and v components of the wind, squaring these differences, adding them, and then taking the square root. While it is true

that stronger bulk wind shear generally results in faster storms, these quantities are not the same and cannot be used interchangeably.

Thank you. The calculation of bulk shear has been fixed.

Minor Comments:

1. Abstract: I am unsure as to the format of the numbers stated in the Abstract. Generally, such precise values are reserved for the body of the manuscript and additional explanation is required as to what these numbers mean. The last paragraph in section 3c is similarly difficult to read or understand.

The precise values (i.e. confidence intervals, p-values, etc) have been removed from the abstract. The bracket numbers are explained in greater detail later in the document.

2. Abstract and elsewhere: The units on bulk shear are m s^{-1}. This is stated incorrectly throughout the Abstract and manuscript.

The units on bulk shear have been corrected to m/s.

3. Section 1, paragraph 3: I am unsure what is meant by "convective energy?" Is this referring to CAPE?

Yes. This is referring to convective available potential energy (CAPE). We corrected this in the manuscript.

4. Section 1, paragraph 3: The terms "speed and directional shear" are obsolete and should be avoided. Hodograph shape is far more important in determining storm type and severity (e.g., Klemp and Wilhelmson 1978; Markowski and Richardson 2010).

"Speed and directional" was removed. It simply states that wind shear is an important factor in the development of tornadoes.

5. Section 2, paragraph 2, second-to-last sentence: I argue that nearly all tornadoes are at least partially a function of their synoptic-scale environment. Please reword this sentence.

We are reticent to call our tornado groups "outbreaks" because we do not link them to a specific synoptic or meso- scale system as suggested in the definition of a tornado outbreak from the American Meteorological Society.

6. Section 2a, last paragraph: Please clearly state the grouping criteria here as is done at the beginning of section 4.

Grouping is based on proximity in space and time. For example, three tornadoes each 100 km apart occurring at the same time are considered a group. A fourth tornado is considered in the group if it is no more than 100 km from any one of the other three tornadoes.

7. Section 3c, paragraph 1: I think the description of the regression model and its interpretation could benefit from additional explanation. For example, as a meteorologist unqualified to teach a college-level course in statistics, I do not follow the 3rd-5th sentences in this paragraph. The remainder of the paragraph could be improved if the units given in the text (TW) matched those on the x-axis of Fig. 7 (GW).

We changed the acronym of ATE because it is not in units of energy. Instead, it is in units of power. Therefore, accumulated tornado energy is now accumulated tornado power (ATP). We converted ATP to units of terrawatts (TW).

8. Section 3d, paragraph 2: I think that a more quantitative measure of geographic preference or area size than simple visual inspection is appropriate here.

The area for each big day was calculated and show no difference.

9. Section 3d, paragraph 3 (and elsewhere): I am not sure what is meant by "efficiency of tornado production." Does it refer to the number of tornadoes produced by a certain storm (or multiple storms) in a certain time? If so, I am unaware of any specific environmental parameters used to forecast it and question its relevance since a single hour-long violent tornado likely causes more damage than several brief, weak tornadoes.

Efficiency of tornado production is defined in Elsner et al 2015 as the atmosphere's ability to produce more tornadoes on a given day (in this case a big tornado day).

10. There are several other grammatical edits throughout the manuscript, but these matters must be addressed first before consideration for formal publication.

Thank you. Corrections have been made.

Reviewer B: James Correia Jr.

Recommendation

Major revision.

There is so much here, even for this short article, but there is much work to do to improve this manuscript. The quest to make ATE a quantitative variable better suited for quantitative study of tornadoes & tornado groups than EF scale, path length, path width is clearly a goal. The follow on goals of showing how we can use ATE to then measure and attribute relative changes over time of the tornado environment I think is the point.

But the story needs fleshing out, clarity, further references, and more analysis. There is plenty of work done to indicate to me that this work has some merit and adds to the body of tornado environment and tornado-trend knowledge.

Summary

Goals:

Quantify the relationship between environmental factors and tornado activity. Produce climo of the big days. (abstract)

How much convective energy is needed to produce a 25% increase in tornado activity?

Data: 1994–2017 tornado data; NARR data (18z) 1994-2014

Methods: spatiotemporal cluster analysis of tornadoes paired with CAPE and bulk wind shear from NARR.
Outcomes: increasing maximum CAPE and shear on tornado days results in increasing ATE by the listed amounts.

Major Comments
1. NARR data and environmental factors has so little discussion and few references. I would like to see you flesh out this discussion since it is imperative to understand the strengths and weaknesses of any reanalysis data set that you wish to draw conclusions from. Environmental factors references specifically with NARR: Gensini and Brooks (2018) for tornadoes, Gensini et al (2011, 2014); Allen et al (2015) for hail.

A paragraph explaining the strengths and weaknesses of the NARR data set was added to the introduction section.

2. Please explain in great detail how using the 18z NARR data is adequate. Surely the limited scope of the big days is worth using the initiation time of the tornadoes, or centroid time for that matter, to fully capture the CAPE present at or during the outbreaks. To address the unique goals of the paper this seems a higher priority for data analysis.
We want to sample the pre-outbreak environment on the big tornado day. Therefore, our Z-times have changed and vary by big day. We choose the nearest 3-hour Z time that occurs prior to the first tornado touchdown on each big day. We can see how many big days fall in each Z-time category in Table 3.
Table 3: Total number of big days associated with each Z time.

Zulu Time	*Number of Big Days*
00Z	*3*
03Z	*0*
06Z	*0*
09Z	*53*
12Z	*38*
15Z	*56*
18Z	*50*
21Z	*12*

3. It appears that you have shown all the work you have done for this research. I would like to see the figures/tables trimmed down so that you may support your findings more concisely and expand the analysis thusly. Lets go through them.
Table 1: While I appreciate the validation to Forbes (2004) this is a multi day analysis and you ended the analysis on single convective days. Perhaps this is worth discussing

without the table that you find some agreement that gives you faith in the cluster analysis across many days.

This table has been removed from the paper.

Figure 1: While I appreciate the sensitivity analysis I find it also an “extra”. You have done your due diligence.

We removed the percent match figure from the paper.

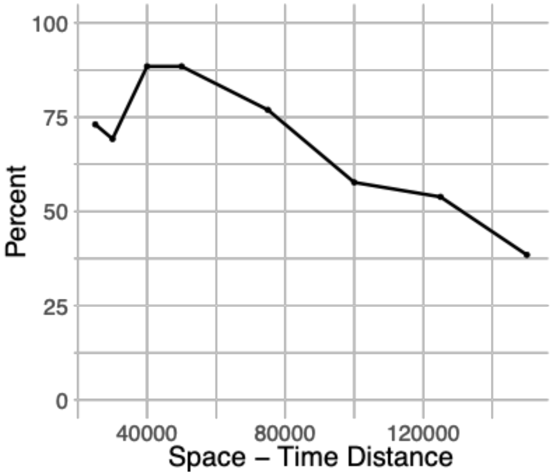


Figure 2: I like this as your lead figure since it clearly relates to your outcome of big days and shows your graphical convex hull in space. Do you have a similar figure for the temporal component? Perhaps the dots can be colorized in terms of hours from start time or hour of the convective day?

This is actually Figure 2 in the paper. We decided that a figure similar to this one, but for our largest groups would be useful. Therefore, Figure 1 is a map of our longest tornado group (5 days) with the dots colored by the convective day. For Figure 2, we colored the dots (tornadoes) by the hour of occurrence. Thank you for the suggestion of adding the temporal component to the maps.

Table 2 & 3: These should be merged

These tables were merged. It is table 2 in the paper.

Table 2: The top ten big days in the largest tornado groups. ATP is the accumulated tornado power on a big day.

Big Day	*Number of Tornadoes*	*Number of Casualties*	*ATP (TW)*
April 27, 2011	*173*	*3069*	*221*
April 26, 2011	*104*	*97*	*46*

January 21, 1999	*99*	*171*	*12*
June 24, 2003	*94*	*12*	*3*
May 5, 2007	*90*	*24*	*8*
May 25, 2011	*90*	*23*	*9*
May 30, 2004	*88*	*46*	*2*
May 4, 2003	*86*	*384*	*31*
February 5, 2008	*85*	*482*	*39*
April 14, 2012	*84*	*79*	*32*

Table 4: Why are we using the average ATE and not the accumulated?

We changed the acronym of ATE because it is not in units of energy. Instead, it is in units of power. Therefore, accumulated tornado energy is now accumulated tornado power (ATP). Accumulated ATP contains information about the number of tornadoes where as average ATP does not. We want to separate these two components of outbreak severity.

Figure 5 and Table 4: Just different views of a similar thing. I appreciate the different perspective but what does this figure add?

The figure shows the values for each big day whereas the table is a sum/average over all big days. The table provides more seasonal information about the big days. The figure (below) is removed.

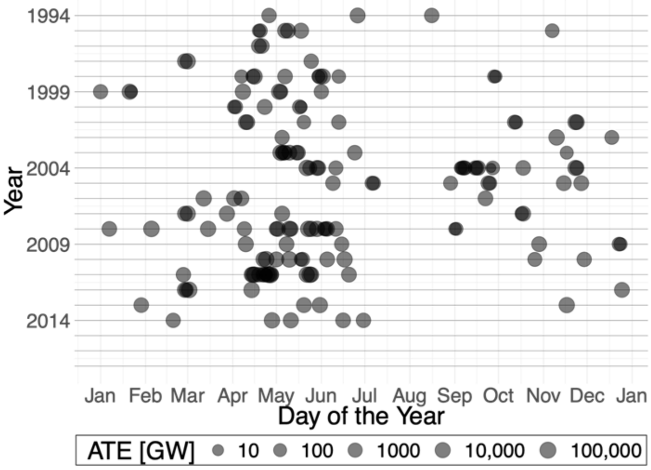
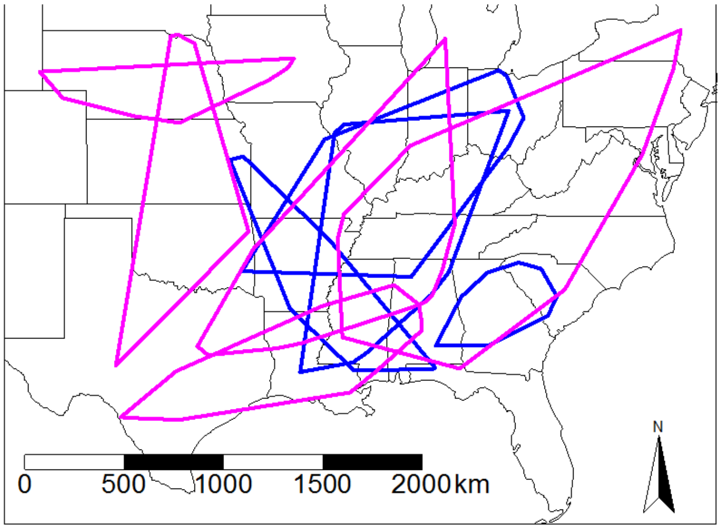


Figure 6 & 7: I appreciate seeing these quantities expressed I am not sure what they add other than a reviewer might request to see them. I am happy to see that you are curious about your data but not all of these need to be present.

These figures were removed from the paper.

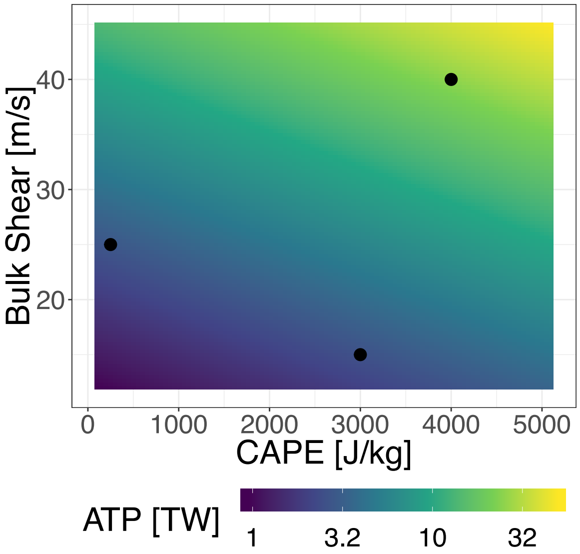
Figure 10: I probably would have asked to see this but after having seen it, a statement about the lack of spatially dependent errors as stated is good enough for this reviewer. Is there a temporal dependence?

Removed. There is no temporal dependence that separates the over- or under-predicted big days.



5. Interestingly, outside the un-visualized model there are no figures showing the distribution of CAPE or shear, or anything related to the two core findings about CAPE and shear.

We add a plot showing a two-dimensional prediction of ATP using CAPE and shear.



6. Regarding the findings, I would like to challenge the second: ATE is useful. How is it useful? In what comparative ways can you describe or reference its usefulness, since you assume/reference its usefulness here. Fricker et al (2017) use power as the metric. Here it is energy. It should not take much discussion to connect the dots, but the dots need to be

connected. Can you summarize the utility of ATE to go beyond the traditional measure of "outbreak severity" and show how it improves the analysis presented here such as in Elsner et al (2014)?

ATP's utility stems from the fact that it is an extensive variable. An outbreak with an ATP of 100 GW has twice the power of an outbreak with an ATP of 50 GW. Fricker et al. (2017) use energy dissipation which has units of power. This is not true of variables like DPI, etc. We use energy dissipation (power) here.

7. Regarding the 2 main findings, you have implied a monthly dependence of some sort. How do your severity increases apply in warm vs cold seasons? Are these findings limited to the warm season where the sample size is largest?

Our model uses month as a random effects term. This allows us to examine how the environmental factors influence tornado power conditional on it being a big day regardless of when it occurred during the year. As you note, since the majority of big days occur during April through June the results are more relevant to these months.

8. Figure 9: I mean it looks OK, because of the 1:1 line until I realized that the model is off by an order of magnitude-ish with ATE? How is this useful here? Likewise Table 3 should have these predicted ATE values in it. They are casually mentioned in the text but never shown.

We added a table on the most over-predicted and under-predicted big days with the actual and predicted values of ATP.

9. You say that helicity doesn't add much. Have you explored the correlations or correspondence of the input environment variables? Then I noticed that you used the storm-motion variables to compute the vertical wind shear? Is that a typo or did you mean you used the storm motion variables to compute the helicity, and the U and V wind components to compute the vertical wind shear? Please clarify.

After adjusting the NARR time for our data, maximum helicity becomes an important factor in predicting accumulated tornado power (ATP) and is added in our model. We had our calculations wrong as Reviewer 1 commented. We use the 0 to 6000 m U and V components of storm motion (layer 324, 325) to calculate the storm motion over the domain. We take the maximum value to represent the big day. For bulk shear, we use the 1000 mb and 500 mb U and V components of wind to compute the vertical shear. We compute the bulk shear as the square root of the sum of the squared differences between the U and V winds for the 1000 mb and 500 mb levels.

Minor Comments

1. There are many figures and tables devoted to ATE. The ATE is new to me yet it is predicated on the path width, of which there are changes to reported path width during the study period, that most tornadoes only briefly experience the maximum path width or even intensity. Thus ATE is a maximum, interpreted by me as an upper bound.

Yes. Power (used to be energy dissipation) can be thought of as an upper bound due to the maximum path width reported with each tornado as well as EF rating. ATP is the summation of power values for all tornadoes on a big day. Therefore, ATP can be thought of as a summation of maximums.

2. Much like the choice in using maximum areal CAPE at 18z. Though without knowing the diurnal cycle of CAPE for the NARR it is difficult to understand how the biases of the NARR might project onto your findings. If CAPE is underestimated, like Gensini et al (2014) found at 00 UTC, then I wonder how bad 18z is? Remember that reanalysis is still partly a coarse model that parameterizes convection. In this way I am unsure how the bias would stack up.

3. Please define the acronym “AIC”.

AIC is the Akaike Information Criterion. It is used in model selection with the best fit model having the lowest AIC value.

4a. What is the value in knowing that the model residuals can be described as normal distribution?

One of the assumptions of a linear mixed effect model (LMER) is that the model residuals are normally distributed. By explaining this, we can verify that our model does not violate the assumptions of LMERs.

4b. There are many statements such as these. They appear and I am expecting some relevant discussion or plot point but then they morph into a new statement. We all tend to think like this but we have to put those plot points together into an analysis. I think you were asking yourself a question, like what does it mean for the slope in figure 9 to not be near the 1:1 line? So casualties are explored. Well what about month like you did in figure 8? Or number of tornadoes? Or number of E/F-2+ tornadoes? Or mean path length? Exploring the data is a wonderful habit to keep. But figuring out the story to tell is much harder. I am having trouble understanding the story you wish to convey.

Reviewer C: John T. Allen

Recommendation: Reject

The authors present an analysis of environmental relationships to accumulated tornado energy produced by large (>30 tornado) outbreaks over the CONUS. Unfortunately, this potentially interesting line of research is beset by a number of issues with the manuscript. The manuscript is challenging to read owing to some language issues related to the use of multiple tenses (particularly the abstract), and by missing references to the standing literature. I am also concerned by the convoluted approach, which makes a number of non-physical choices for the ‘proximity’ environmental data used and how this characterizes the event, through to the problems with selection methodology for outbreaks. As there a number of studies out there that haven’t really been considered to provide context here (including at least one by one of the authors), my recommendation to the authors is to carefully consider the relevant literature in more detail, and ensure that they are following best practices when considering a new direction. At the current stage the manuscript is not acceptable, and in my view, substantial additional analysis to improve the quality of the analysis and results along with rewriting is required, hence I would recommend rejection with the potential for resubmission, as this manuscript has the potential to fit within the topics covered by EJSSM and eventually be an interesting contribution to the literature. My comments supporting this recommendation are provided below, though are not exhaustive, as following the methodological issues, the results are of questionable impact.

Major Comments:

1. **Language in abstract and at times in the introduction is not consistent with a journal submission.** In subsequent submission this needs to be addressed. One does not talk about 'the authors' in any abstract submitted in a journal publication. The authors should be careful with the use of tense, and ensuring the language is precise.

I have removed the use of we, they, and the authors from the abstract.

2. **Literature review is limited and does not reflect the current state of the science.** A number of studies have considered the conditions leading to tornado outbreaks – beyond the cited Galway (1977), and Dean (2010) – see Dean and Schneider (2012), Grams et al. (2012), Anderson-Frey et al. (2018) among others. The authors need to conduct a more thorough assessment of the literature. To give a few examples – they should also consider studies that look at outbreaks/ big days e.g. Elsner et al. (2015), Tippett et al. (2014), Mercer et al. (2009) which all discuss the classification of outbreaks, a point which the authors seem to overlook.

The citations were updated to explain the conditions that are influential to tornado development. An additional paragraph was added on tornado days.

3. **Paragraph 3, page 1 and general premise. Assessing the quantifiable increase** in a parameter to assess the increase in tornado activity is extremely problematic. It a priori assumes that there is a clear linear relationship with these environmental parameters, rather than considering the role of forcing or other important factors (using bulk data this is simply untrue – see Grams et al. (2012) for example for the spectra of environments that favor the typically fatal tornadoes). Furthermore, it is well known within the community that there tends to be a host of factors that play into tornado formation from an environmental perspective (Thompson et al. 2007, Thompson et al. 2012, Grams et al. 2012, Sherburn et al. 2016, Anderson-Frey et al. 2018) – are two simple parameters, choosing only the max/min within the convex hull defined for an outbreak going to capture this response variance?

Yes, we realize there are many factors related to the severity of tornado outbreaks. But we also know that CAPE and shear are two important ones. Our goal is to quantify the degree to which these two factors play a role. As an analogy we know there are many factors related to cancer rates but examining the role of just one (e.g., smoking habits) can provide us with a better understanding of this important factor.

It should also be kept in mind that we are not interested in tornado formation per se. We do not consider null cases where tornadoes failed to form. We are interested in aggregated tornado power at the outbreak level. What factors contribute to variations in this power? Our approach somewhat of a new perspective on an old problem.

4. **Definition of a tornado outbreak in the introduction.** The reference to Malamud is a bit problematic – there are many, many other papers that provide a definition on outbreaks, with considerable argument to this effect. See Mercer et al. (2009), Tippett et al. (2014), Elsner et al. (2015) for examples, among others. These papers should be cited if the authors are going to make a somewhat arbitrary choice which influences sample size. Furthermore, it is stated by the authors that a tornado outbreak can span 'short as an hour to as long as several days'. This is incorrect in the light of the literature – an outbreak is typically confined to within a day, with a set of several days generally referred to as an outbreak sequence or a multiple-day event. 30 tornadoes over a couple of days has far less significance than 30 on a single day. See Trapp (2014) for a discussion on this topic. At the very least the authors need to be careful in their descriptions here.

The citations were added to the definition of an outbreak. The definition is meant as an informal overview of an outbreak. We are not looking for specific values on a given day as mentioned in the papers mentioned above.

We have adjusted our explanation of an outbreak. We now state that "A tornado outbreak is generally confined to a single day; however, consecutive outbreak days result in an outbreak sequence or a multi-day event".

We use 30 as an arbitrary number to extract our big groups. We are not looking for 30 or more tornadoes on a given day. Our study focuses on big days (10 or more tornadoes) that occur in a large group (30 or more tornadoes). Therefore, we extract the most prolific days that occur in these large multi-day events.

5. **Methodology:**

Event selection: as far as I can read from the manuscript, the initial groupings for 'large events' only require groupings meeting the 100K threshold for at least 30 tornadoes (EF0+) but can span over the course of up to 9 days. This is really not a great metric for selecting outbreaks, as the threshold is rather low (just over 4 weak tornadoes per day for example could qualify an eight-day event). I would light to see greater details of the events selected and their duration as part of justifying this approach. Speaking specifically of clustering methods, mention of Mercer et al. (2009) here is also a given. While the authors refine this to the big 24 hour periods in the subsequent section, I remain skeptical of the initial approach, owing to the potential of different formative mechanisms within a cluster – even on the same day. Moreover, the lack of criteria to distinguish between days that produce many weak, and those that are stronger tends to questioning the impact of some of these events – this probably explains why the dataset is so weighted toward the recent past (more tornadoes), and there are relatively few fatalities in some of the events (Table 2).

The final grouping is actually 50,000 space-time units. The longest event is 5 days. The majority of our events are 1 to 2 day events. 30 or more tornadoes were chosen to represent large groups. We are not interested in these groups specifically. Our study focuses on big days (10 or more tornadoes) that occur in a large group (30 or more tornadoes). A table was added to show the varying events, duration, and number of tornadoes.

Table 1: The total number of events and tornadoes by the duration of our large groups.

Duration (days)	*Number of Events*	*Number of Tornadoes*
1	*46*	*2024*
2	*83*	*4461*
3	*22*	*1620*
4	*3*	*197*
5	*1*	*103*

The severity of the big days is captured by accumulated tornado power (ATP). Power (P) is calculated for each tornado on a big day. The P for all tornadoes on that day is summed providing a value of ATP on that day.

Environmental Selection: The variable selection reflects simply collecting data from the archive – while that's fine, it is important to realize that 180mb CAPE isn't really a great choice on a sub-daily scale, as it reflects overly deep mixing through the troposphere (particularly relevant over the SE) – hence why much of the community uses 100 mb or surface based in some situations. Considering both a surface based parameter and the mixed-layer parcel would be worthwhile.
The end date of NARR is not 2014, just the NCEI archive version – rather an archive version is kept at the RDA maintained by UCAR - see https://rda.ucar.edu/datasets/ds608.0/ for available data.

We switched to the RDA from UCAR. Our data ranges from 1994 to 2017.

Other concerns: 2pm EST/1pm Central is not the peak time for tornado activity, and thus the authors choice of 18UTC is incorrect as a proximity characterization. See Krocak and Brooks (2018 their Figure 7) which clearly demonstrates this argument and Anderson-Frey et al. (2018, their Figure 2) – the timing is later in the afternoon evening – generally between 2 hours before and 2 hours after sunset, even in the SE where the threat persists into the evening. The authors should have considered either 21UTC or 00UTC as this corresponds to a proximal dataset in NARR, and this approach is more consistent with earlier research on this topic.

We want to sample the pre-storm environment of the big tornado day. Therefore, our Z-times have changed and vary by big day. We choose the nearest 3-hour Z time that occurs prior to the first tornado touchdown on each big day. You can see how many big days fall in each Z-time category in Table 3.

Table 3: Total number of big days associated with each Z time.

Zulu Time	*Number of Big Days*
00Z	*3*
03Z	*0*
06Z	*0*
09Z	*53*
12Z	*38*
15Z	*56*
18Z	*50*
21Z	*12*

Another problem with this approach is to characterize the environment based on the maximum/minimum within the domain of the convex hull. It has been well demonstrated that a variety of regimes can produce tornadoes, even on a given outbreak day – and the spatial width of some of the convex hulls suggest that a mixed modal structure is possible – for example, tornadoes associated with a triple point, along a warm front and along a dryline can occur within a single convex hull or QLCS versus Supercell derived on the same day (e.g. Thompson et al. 2012). What is to say that the environmental parameters max/min is going to have skill in characterizing this? Thus I would argue that this approach really isn't valid for characterizing the outbreaks individually, and is further compounded by the fact that the proximity time does not correspond to the peak of diurnal instability generation.

We are sampling the pre-outbreak environment. The maximum value is chosen because CAPE and shear values can differ spatially and temporally on a big day. If we took the average, you would wash out the values of CAPE and shear that occur over the domain of the outbreak. Taking the maximum/minimum values allows for a more representative sample of the environment producing these events. It also removes the influence of other local or meso-scale features. We are not distinguishing between events caused by synoptic or mesoscale features.

General Comments:

First paragraph, Pg 1: Part of this signature is the clustering of big tornadoes to outbreak days – the days which favor many tornadoes tend to also accumulate the strong tornadoes that have the strongest relationship to fatalities. A reference to Mercer et al. (2009) is appropriate here.

I added a sentence about the relationship between strength of the tornadoes and casualties with the Mercer et al 2009 citation.

Second paragraph, Pg 1: Yes, tornado outbreaks are well documented, yet the authors fail to mention the appropriate studies, rather refer to grey literature and older studies. Please consult other suggested literature.

The literature review was expanded.

Paragraph 1, Pg 2: An appropriate reference for the proximity approach would be Rasmussen and Blanchard (1998), or perhaps Potvin et al. (2010) who discuss the proximity criteria that should be used for this approach explicitly. It is also questionable if this approach really reflects a 'proximity' study.

This study does not utilize proximity soundings. The point of this paragraph is to show that soundings are not representative of large scale environments consistent with an outbreak.

Paragraph 1, Pg 2: In addition to the LSHC/LCHS – you should cite appropriate literature that covers this from the recent past – e.g. Sherburn et al. (2016) for example, or other studies mentioned above.

Recent literature on low shear/high cape and low cape/high shear events were incorporated into the paragraph.

Top paragraph RHS, Pg 2: It should be 'synoptic- or meso-scale system' as many tornado outbreaks occur associated with localized features or boundaries as well, this definition is under revision at AMS.

As the definition of an outbreak is a definition from the current AMS glossary, I added an additional sentence on how outbreaks are also associated with mesoscale features such as supercells, dry lines, and other features.

3rd paragraph RHS, Pg 2: 'The space difference is divided by ten so the magnitude is commensurate with the corresponding time difference under the assumption that, on average, thunderstorms move at ten meters per second.' I'm confused what the authors are suggesting here? Is this really the typical average speed of motion for thunderstorms – 22 mph? This would seem to be low, particularly given it is well established that tornadoes on outbreak days tend to establish the longest path lengths due to the strong vertical wind shear and resulting fast storm motions (35-70 mph).

We examined the sensitivity of using divisors between 10 and 30 and found no large difference the clustering of outbreaks. Additionally, we calculated the average storm motion on all big days and found 15 m/s as the average. Therefore, we now divide by 15 to keep consistent with our calculated value of storm motion.

2nd Paragraph RHS, Pg 5, There are other references to the use of CAPE and Shear which the authors could easily find and add here. See above literature.

We expanded the literature review.

1st Paragraph, Pg 7, ATE section: 'On the other hand, the annual average ATE appears to be increasing with the higher values occurring later in the period.' – This is somewhat difficult to justify given the large spread in the data, and the shifts in the time series. This point should be removed and the paragraph finished with the no-trend statement.

ATP is increasing later in the period as shown by our models. Figure 5 is our argument for using year as a predictor variable (fixed effect) in our model.

2nd Paragraph, Pg 7: This is simply a questionable approach – a single parameter, chosen from not even a clear proximity location to the tornadic event is going to provide extremely limited utility for any sort of prediction even on a regional accumulation – and the low correlations would argue for this limited utility.

We do not use proximity soundings in this study. We use NARR data over the domain of the big day to extract the maximum/minimum values of our environmental factors. This provides a more representative environment of our big days.

Table 5: The standard errors here are very large relative to the estimated parameters, which is unsurprising given the approach.

Using our new approach the SE is smaller.

Figure 2: The polygon color and the caption do not seem to match.

Fixed.

Figure 6: Error in figure caption – start date.

This figure was removed.

Suggested References: *We have added many of the suggested references. Thank you.*

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