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A Climatology of Long-Track Tornadoes

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ABSTRACT

A 40-year climatology (1979–2018) is presented for long-track tornadoes in the United States using the Storm Prediction Center tornado database. Path length (PL) stratification thresholds are defined using characteristics of supercell storm evolution, and are categorized as: all (ALL), PL >0 mi or 0 km; short (S), PL <30 mi or 48.3 km; long (L), [30, 60) mi or [48.3, 96.6) km; very long (V), [60, 90) mi or [96.6, 144.8) km; extremely long (X), PL ≥90 mi or 144.8 km; and long-track sum (LVX), PL ≥30 mi or 48.3 km. Results show LVX tornadoes: a) made up <1% of all tornadoes; b) occurred east of the Rocky Mountains; c) were generally wider; d) caused disproportionate numbers of deaths and injuries; e) typically had damage ratings ≥F/EF2 (peak F/EF3); f) occurred more often with more deaths and injuries in the Southeast than in the Midwest or Great Plains; g) had larger area scale and Destruction Potential Index; h) occurred mostly in April and May versus May and June for S tornadoes; i) occurred primarily from midafternoon to early evening; j) had a peak formation hour at 1600 local solar time (also true for ALL S, V and X), though L tornadoes had a peak and secondary peak at 1800 and 1500, respectively; k) were less common during nighttime than S tornadoes; l) were more frequent during nighttime in the Southeast than nighttime in the Midwest or Great Plains; and m) occurred more often with tornado outbreaks.

1. Introduction

Consideration of long-track tornadoes, which make up a very small percentage of all tornadoes, is crucial because they cause a disproportionate loss of life and property compared to short-track tornadoes (e.g., Wilson and Morgan 1971; Kelly et al. 1978, K78; Garner 2007, G07; Doswell et al. 2006, D06; Garner et al. 2021, G21). Long-track tornadoes affect larger areas, with typically higher damage ratings, compared to vastly more common short-track and lower damage-rated tornadoes (e.g., Wilson and Morgan 1971; Abbey and Fujita 1975; K78; Brooks 2004, B04; Elsner et al. 2014, E14). Historically, no prior multidecadal, general tornado climatology (e.g., Wolford 1960; K78) has focused specifically on tornado path length (PL), though PL has been considered as a sub-category. The purpose of this study is to present a new, four-decade climatology from 1979–2018 to assess tornadoes in terms of PL stratification, in the context of long-track tornadoes.

Tornadoes are often described in the literature as "weak", "strong," or "violent" tornadoes (e.g., K78) based on damage-rating descriptions from the Fujita damage-rating scale (F scale; Fujita 1971, F71; Fujita and Pearson 1973, FP73) before 2007 and the Enhanced Fujita damage-rating scale (EF scale; McDonald and Mehta 2004; Edwards et al. 2013) after 2007, at least in the United States (F/EF herein reflects use of F and EF scales). Unfortunately, an analogous, physical evidence- or statistical-based scale describing long-track tornadoes does not exist, nor does one exist for tornado longevity. Some studies that considered tornado PL stratifications and/or defined long-track or very long-track tornadoes are shown in Table 1.

Research (e.g., those studies included in Table 1 and others) has indicated that tornado PL is related to loss of life and property. Additionally, none of the PL stratification

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thresholds for tornadoes in Table 1, which vary by an order of magnitude with a range from 20–180 mi (32.2–289.7 km), has a physical basis. Many of the PL thresholds for long-track tornadoes for these studies seemingly were selected independently of one another, suggesting a lack of general agreement. There has been a more recent use of PLs closer to 20 mi (32.2 km), usually to increase sample size, rather than the much longer-PL thresholds for long-track tornadoes used more than two decades ago. In contrast, Abbey and Fujita (1975), Tecson and Fujita (1979), B04, Agee and Childs (2014) and E14 considered a spectrum of PLs without stratification in their studies.

Tornado PL stratifications convey information and expectations associated with physical factors that control the PLs and their frequencies. In some instances, a physically based stratification for tornado PLs can be preferable to an arbitrary statistically based one, such as that used by G21. When tornado PL stratification categories are based on physical storm characteristics, this informs the understanding of relevant storm dynamics by forecasters and researchers. In contrast, an arbitrary statistical tornado PL stratification definition does not provide information about relevant physical storm characteristics that control the PLs.

An example of a study in which tornado PL was helpful in revealing supercell storm dynamics is that of Dowell and Bluestein (2002). They showed that, for a tornadic supercell storm on 8 June 1995, in McLean, TX, initial, shorter-PL tornadoes were related to the quickly cycling mesocyclones. The storm subsequently evolved into non-cyclic morphology and produced a longer-track, long-lasting tornado. In analogy to the F/EF and the Saffir-Simpson scales (Saffir, 1973; Simpson 1974), which are based in part on the actual or possible damage produced by tornadoes and hurricanes, the use of a physically based PL stratification (e.g., short, long, very long and extremely long PLs) could also provide expectations for the potential loss of life and property. Longer tracks are associated with greater risks and larger affected areas.

Both long-track and long-duration tornadoes are uniquely important from tornado climatology, dynamics, forecasting and risk-assessment perspectives. Efforts to define a tornado as long-track and/or long-lived are complicated by the interdependency of PL, tornado translation speed and path duration (PD). Most long-track tornadoes are considered long-

Table 1: Prior studies that included tornado path length (PL) and thresholds for long-track and very long-track tornadoes.

Study	**PL Stratifications (if provided)**	**Long-Track PL Thresholds mi (km)** **Very Long-Track PL Thresholds mi (km)**
Wolford (1960)	<0.5, 0.5–5, 5–10, 10–20 and >20 mi (<0.8, 0.8–8.0, 8.0–16.1, 16.1–32.2 and >32.2 km)	≥180 mi (289.7 km)
Wilson and Changnon (1971)		≥150 mi (241.4 km)
Wilson and Morgan (1971)		≥100 mi (160.9 km) ≥150 mi (241.4 km)
Fujita and Pearson (1973)	0.3–0.9, 1.0–3.1, 3.2–9.9, 10–31, 32–99, 100–315 mi (0.5–1.4, 1.6–5, 5.1–16, 16.1–50, 51.5–159, 160–507 km)	≥32 mi (51.5 km)
Kelly et al. (1978)	0–3.1, 3.2–31, ≥32 mi (0–5, 5.1–50, ≥51.5 km)	≥32 mi (51.5 km)
Broyles and Crosbie (2004)		≥25 mi (40.2 km)
McCarthy and Schaefer (2004)		≥100 mi (160.9 km) ≥150 mi (241.4 km)
Passe-Smith (2006)		≥20 mi (32.2 km)
Doswell et al. (2006)		≥49.7 mi (80 km)
Garner (2007)		≥25 mi (40.2 km)

duration tornadoes (e.g., G07), which are defined here as having PD ≥30 min. Thus, PL is often used as a proxy for tornado longevity, which is based on tornado beginning and end times. From a pragmatic view, tornadoes can be either, or both, long-duration tornadoes and long-track tornadoes (e.g., a long-lived tornado is not always a long-track tornado and vice versa). Some very fast-moving, long-track tornadoes might only last for <15 min, while some very long-lasting tornadoes might travel <30 mi (48.3 km). For example, a tornado with a path of 20 mi (32.2 km), which lasts for 60 min translating at 20 mph (8.9 m s^{-1}), is more substantial in terms of PD than a tornado with a PL of 40 mi (64.3 km), which lasts for 40 min translating at 60 mph (26.8 m s^{-1}), but perhaps not with respect to potential damage. Unfortunately, PD cannot be studied in this 40-y climatology. Complete and accurate tornado PD estimates before 2014 are largely unavailable from reports and are not possible to obtain from pre-2014 WSR-88D, WSR-74 or WSR-57 radar data, even using the Supplemental Adaptive Intra-Volume Low-Level Scan technique (SAILS; Chrisman 2011; Smith et al. 2020a, b).

The methods and data are described in section 2. A proposed evidence-based stratification of tornado PLs based on supercell storm mesocyclone evolution is presented in section 3, including tornado track PLs classified as: all (ALL), PL >0 mi or 0 km; short (S), PL <30 mi or 48.3 km; long (L), [30, 60) mi or [48.3, 96.6) km; very long (V), [60, 90) mi or [96.6, 144.8) km; extremely long (X), PL ≥90 mi or 144.8 km; and long-track sum (LVX), PL ≥30 mi or 48.3 km[1].. The results of the tornado climatology based on the proposed PL stratification for the United States from 1979–2018, including examinations of the path width (PW), F/EF scale, geographic regions and states, months, hours, and associated deaths plus injuries, with a focus on long-track tornadoes, are presented in section 4. Nighttime long-track tornadoes are discussed owing to the deadliness of nocturnal tornadoes (e.g., Ashley et al. 2008). Finally, the summary and conclusions are presented in section 5.

2. Data and methods

The data used for the tornado PL climatology in this paper are from the tornado database maintained by the Storm Prediction Center (SPC; https://www.spc.noaa.gov/wcm/#data). Additional data from the NCEI, as well as information compiled by Grazulis (1993; 1997) were considered for specific cases.

Limitations of and changes in database reporting are important to consider in the interpretation of any tornado climatology (e.g., Brooks et al. 2003; McCarthy 2003). These include the apparent increase in the number of reported tornadoes over time, presumably influenced in part by improved reporting, increased awareness and the advent of Doppler radar (e.g., Changnon 1982; McCarthy and Schaefer 2004; Verbout et al. 2006; Anderson et al. 2007; Edwards et al. 2013; Agee and Childs 2014; Coleman and Dixon 2014; Farney and Dixon 2014). Furthermore, population centers can bias the number of reported events (e.g., McNulty 1981; Passe-Smith 2006; Elsner et al. 2013). Additionally, human errors in data entry or parameter misconceptions also exist (K78, Changnon 1982; Doswell and Burgess 1988; Grazulis 1993, 1997; McCarthy 2003; Brooks et al. 2003; B04; McCarthy and Schaefer 2004; Verbout et al. 2006; Coleman and Dixon 2014; Zenoble and Peterson 2017). Smith et al. (2012) and Edwards et al. (2012) also note time and location errors (e.g., time entries being 1 h off).

Issues related to the assignment of damage ratings to tornadoes, owing to subjectivity and/or the existence of different strengths of affected structures, have been discussed by, for example, Doswell and Burgess (1988); Edwards 2003; Doswell et al. (2009); Edwards and Brooks (2010); and Edwards et al. (2013). More recently, Edwards et al. (2021; EBC21) identified minor inflation of EF1 and EF2 ratings at the apparent expense of EF0, following the introduction of the EF scale in 2007.

The meaning of PL continuity is partly philosophical in nature and its determination subjective (e.g., McCarthy and Schaefer 2004). Tornado-PL continuity has been questioned when tornadoes were described as “skipping” (Battan 1959; Schaefer et al. 1986; McCarthy and Schaefer 2004; Nixon and Allen 2021), or

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[1] Mathematical interval notation is used herein to denote inclusivity or exclusivity of endpoint values in a numeric range (also called open or closed intervals). The range is inclusive of the endpoint value when denoted with a square bracket and exclusive of the endpoint value when denoted with a parenthesis. For example, [A, B) denotes a range that includes A but not B; that is, the range of values that are ≥A but <B.

actually were multiple tornadoes associated with tornado families (Wolford 1960; Howe 1974; Doswell and Burgess 1988; Adlerman et al. 1999). Highlighting the issue of PL continuity is the Tri-State (Missouri/Illinois/Indiana) tornado on 18 March 1925, which is recognized as the longest track tornado in the United States by the NWS, with a PL of 219 mi (352 km) and a duration of ~210 min (NWS 2022). A comprehensive investigation of the Tri-State damage track suggests the longest continuous PL segment may been as little as 151 mi (243 km) to as much as 235 mi (378 km), but most likely ≥174 mi (280 km; Johns et al. 2013). Kelly et al. (1978), B04 and Zenoble and Peterson (2017) also have questioned the tornado PL and PW accuracies in the database. Moreover, EBC21 identified a slight increase in mean tornado PLs and substantial increases in PWs, coincident with the EF damage-rating era.

To examine the accuracy and consistency of the PL data, the PL for all tornadoes with PL ≥60 mi (96.6 km) in the SPC database was compared with NCEI Storm Data, information from Grazulis (1993; 1997; T. and D. Grazulis 2021, personal communication), NWS office records available online and WSR-88D data. Most SPC PLs were in agreement with the various data sources to within 4 mi (6.4 km). Differences probably were most often due to the use of point-to-point distances versus actual PLs that likely were curved (and perhaps to typographical errors in some cases).

There were five questionable X tornado PLs from this analysis. Three of them possibly were associated with families of tornadoes (Grazulis 1993, 1997). Another is the 103.5 mi (166.6 km) PL, 3–4 April 1981 Iowa tornado, rated an F/EF0 and also reported as a “mostly skipping” tornado. That is very likely in error because of the unphysical track obtained by plotting the segment data from NCEI Storm Events database (NCEI 1981). The inconsistency of the PL associated with the fifth questionable X tornado is unknown owing to a lack of more complete data. Finally, the SPC database PL of the 80 mi (128.8 km), narrow PW (80 yd or 73.2 m), 22 April 2004 Oklahoma, F/EF0, V tornado was mostly likely in error as the stated PL from the NWS (2004) was 0.8 mi (1.3 km) and an examination of the KINX (Tulsa, OK) WSR-88D radar data by the authors did not support a long-track tornado. Other V and X tornadoes prior to 1979 had some inconsistencies.

To help quantify these PL uncertainties and detect any issues with all tornado PLs ≥30 mi (48.3 km) in the database, the difference between the reported lengths and the distance calculated for cases with known beginning and ending latitude and longitude was calculated. The differences were binned for 1, 2, 4, 8, 16 and 32 mi (1.6, 3.2, 6.4, 12.9, 25.8 and 51.5 km). Differences of ≥4 mi (6.4 km) were found for 22.6% (95), 21.2% (78), 23.1% (12) and 35.7% (5) of the LVX, L, V and X tornadoes (percent of total in each PL category). Further investigation of these 95 LVX cases in the database showed that at least 3%, 3%, 4% and 20% for LVX, L, V and X tornado PLs, respectively (affecting at least 40 entries), were possibly families of tornadoes, erroneous or had obvious typographical errors, when compared with NCEI, information from Grazulis (1993, 1997), NWS office summaries and WSR-88D data.

This approach to evaluate PL accuracy cannot account for curved or irregular paths, and certainly was not meant to find all errors. Rather it was meant to find inconsistencies to document a limitation of the PL data. Importantly, we did not filter the data based on this analysis; the SPC PL data were used without alteration. Further investigation into these cases is unlikely to lead to many solid rectifications, owing to a lack of more information. Fortunately, the extent of these discrepancies is such that they do not grossly change the qualitative and quantitative results reported in this study. With this in mind, for this study, PLs in the database are taken to be correct and continuous, acknowledging that some might be combined paths in a tornado family, not reflecting curved tracks, or otherwise erroneous.

Multistate continuous-track tornadoes were counted only once using segment flags in the dataset. The database was further filtered by removal of: a) cases that occurred in Alaska, Hawaii, U.S. territories and the District of Columbia; b) entries with PL = 0 mi (0 km); and c) tornadoes with unknown F/EF damage ratings. Such filtering removed 279 (<1%) tornadoes from the database, all of which were S (or PL = 0) tornadoes. All geographically based statistics were computed using the states and regions in which tornadoes formed.

The local solar-hour computation was made with the form of the equations in Duffie et al. (2020) for the entire database using the SPC reported tornado start time in CST (converted to local standard time), day, month, year, and latitude and longitude. Results of the local solar-hour calculations were <1 min different from those found using the NOAA online calculator (https://gml.noaa.gov/grad/solcalc/). Note that slight differences in the forms of the equations used to compute local solar time resulted in time differences generally <1 min. These different forms very slightly affected the hourly statistics for shorter-track tornadoes, but did not affect the statistics for tornadoes with PL ≥30 mi (48.3 km) in this study. In summary, the hour, day, month, and year in which a tornado formed were determined using local solar time, as defined above.

Different definitions of nighttime have been used in different ways in previous climatologies, including dividing the time between sunrise and sunset into 12 equal intervals (K78); 10 pm to 6 am local time (Simmons and Sutter 2005); sunset to sunrise (Ashley 2007); 2 h after sunset to sunrise (Ashley et al. 2008, who note that in storm environments, it is relatively dark before sunset); 2100 to 0700 the next day (Kis and Straka 2010); and local sunset to sunrise (Mead and Thompson 2011).

Nighttime for the present research was defined when the position for the top of the sun was below the horizon. The solar position (center of the sun) was calculated by an accurate subsolar point method proposed by Zhang et al. (2021). This calculation uses the original SPC reported tornado start time in CST (converted to UTC time), day, month, year, and latitude and longitude. The calculated solar positions resulted in sunsets and sunrises that were generally <1 min from the solar positions determined from NOAA (https://gml.noaa.gov/grad/solcalc/azel.html and its newer version, https://gml.noaa.gov/grad/solcalc/). Using the calculated solar position and Sun's angular radius = 0.5334˚/2, nighttime was defined herein as the time when the top of the sun was just below the horizon to the time when the top of the sun was just above the horizon. Daytime was determined to begin when the top of the sun was just above the horizon until top of the sun was just below the horizon. Daytime climatology results were similar in most cases to those of 24h due to sample-size dominance (daytime tornadoes constituted 71.9% of all tornadoes in the dataset) and thus are not shown except in Fig. 1.

The determination of the integer hours in which tornadoes formed was based on the calculated local solar time. Hereafter, all times are given in local solar time unless otherwise noted. Tornadoes starting between HH:00 to HH:59 were counted as starting during the local hour of HH. The effect of a possible early bias this method creates in interpreting tornado formation times has not been quantified. Some long-track tornadoes last 1–2 h or more. Therefore, the integer-hour start time does not completely represent all of the hours affected by long-track tornadoes. This applies to the deaths and injuries as well.

The SPC tornado database used mean tornado PW prior to 1995 and maximum PW starting in 1995 (B04). Furthermore, EBC21 document increasing PWs in the EF era, from 2007. To make the PWs in these three periods more compatible, PWs from 1995–2006 and 2007–2018 were multiplied by the ratio of the mean PW from 1979–1994 to each of the mean PW from 1995–2006 (≈0.833) and 2007–2018 (≈0.485), respectively, so that the entire record more closely matches the mean PW. In contrast, in their development of a tornado destruction index, Agee and Childs (2014) adjusted the mean PWs prior to 1995 upward to be consistent with maximum PWs starting in 1995.

The sum of the number of deaths plus the number of injuries from each tornado was used to examine the impact of tornadoes on human lives. Tornado injuries generally occurred most prominently in the same months and hours as did deaths. Therefore, the results using the sum of the numbers of deaths and injuries was similar to those using the number of deaths and injuries examined individually. With respect to time and location, the deaths and injuries are plotted using the recorded tornado start time and location.

The results of this study are limited by the small sample sizes of the V and X categories, and to some extent the L category, especially for the nighttime subsets. Also, the combination of small sample sizes with interannual variability further precludes discerning meaningful long-track tornado temporal trends from the data. Finally, the results are likely be affected by reporting and recording errors to an unknown degree. Thus, caution should be taken when making generalizations.

3. Tornado path length and duration stratification

Longer-PL and longer-PD tornadoes most often are associated with supercell storms (e.g., G07; Smith et al. 2012; Edwards et al. 2012; G21), which have isolated, long-duration, steady and nearly continuous updrafts. A possible limitation of using this assumption is that a few longer-PL and/or -PD tornadoes have been reported to have been associated with bow echoes (e.g., Agee et al. 1976), quasi-linear convective system (QLCS; e.g., Trapp et al. 2005), or mesoscale convective vortex (MCV) characteristics (e.g., Anderson 1985). Those are less likely to have isolated long-duration, steady, nearly continuous updrafts than supercell storms.

Garner (2007) showed storms producing long-track tornadoes (PL ≥25 mi or 40.2 km) moved on average at 44.7 mph (20 m s^{-1}), while storms producing shorter-track tornadoes (PL <25 mi or 40.2 km) moved on average at 26.8 mph (12 m s^{-1}), which supports the association between long-track tornadoes and faster forward speeds. In contrast, some notable examples of long-duration tornadoes covering <30 mi (48.3 km), but lasting longer than one hour include: a PL = 29 mi (46.7 km) and PD = 72 min F/EF4 tornado near McLean, TX on 08 June 1995, translating at 24.2 mph (10.8 m s^{-1}; Dowell and Bluestein 2002); a PL = 22 mi (35.4 km) and PD = 65 min EF5 tornado near Greensburg, KS on 04 May 2007, translating at 20.3 mph (9.1 m s^{-1}; Bluestein 2009); a PL = 2.33 mi (3.7 km; NCEI 2022) and a PD = 60 min F/EF3 tornado near Bennington, KS on 28 May 2013, translating at <0.67 mph (0.3 m s^{-1}; Wurman et al. 2014); and a PL = 26 mi (41.8 km) and PD = 93 min F/EF4 tornado near Niles, KS on 25 May 2016, translating at 16.8 mph (7.5 m s^{-1}; NWS 2016).

Parent supercell mesocyclones (e.g., Lemon and Doswell 1979; Burgess et al. 1982; Dowell and Bluestein 2002; Bunkers et al. 2006a, b; Marquis et al. 2012) from which long-track tornadoes and long-duration tornadoes form, necessarily need to last at least as long as the tornadoes they produce. Additionally, long-PL and/or long-PD tornadoes are assumed to be associated with only their original parent mesocyclone and updraft from which they form for the entirety of their durations, while allowing for updraft mergers (Kurdzo et al. 2015). Long-tracked, long-lived parent supercell updrafts are required for long-track tornadoes. Similarly, long-lived supercell updrafts are required for stratifying long-duration tornadoes. Bunkers et al. (2006a, b) define short-lived supercells as having duration <2 h and rarer long-lasting supercells as having duration >4 h (some have had duration >8 h). Garner (2007) showed that storms with tornado PLs ≥25 mi (40.2 km) lasted for a mean of 4.7 h versus 3.1 h for those with tornado PLs <25 mi (40.2 km). This supports the concept that long-track tornadoes are associated with longer-lived storms. A recent example was a supercell that lasted for >7 h on 10 December 2021 and produced at least two tornadoes [one with PL = 80.3 mi (129.2 km) and one with PL = 165.7 mi (266.7 km)] as it tracked through Arkansas, Missouri, Tennessee, and Kentucky (NWS 2021).

The temporal length of observed supercell mesocyclone cycles is highly variable. For example, Darkow and Roos (1970) documented a large number of tornadic supercells in Missouri that produced multiple tornadoes with cycles 20 min to 2 h, with an average of 45 min. Based on radar observations, Burgess et al. (1982) concluded that 24% of mesocyclones were cyclic supercell mesocyclones, with cycle periods of roughly 40 min. They noted that the first mesocyclone cores might take the longest to form, with shorter successive cycles. The McLean, TX supercell (Dowell and Bluestein 2002) observed during VORTEX (Rasmussen et al. 1994) produced a family of tornadoes and transitioned from initial cyclic behavior associated with three successive shorter-lived (PDs of 23, 12, and 2 min) tornadoes, to non-cyclic behavior associated with a fourth tornado, which lasted 72 min.

Given the limitations and incomplete observational knowledge of cyclic behavior of tornadic supercells, numerical models have been used to improve information gaps, though with many limitations. For example, in a numerical study of cyclic and occluding low-level mesocyclogenesis, using 500-m grid spacing, Adlerman et al. (1999) found a 60-min cyclic mesocyclone period, but using 105-m grid spacing, the cycle was reduced to 45 min (Adlerman and Droegemeier 2002). In the latter study, they showed a wide variation of cyclic periods from 20 min to >120 min. In addition, simulated supercell cycles can be highly dependent on hodographs, as well as model resolution, numerics, and physics (Adlerman et al. 1999; Adlerman and Droegemeier 2002, 2005). More recently, Markowski (2020) also showed variations in initial PBL perturbations in supercell simulations resulted in significant sensitivity with "very limited intrinsic predictability" of tornado-like vortices, related to supercell cycles. Observations suggest no obvious dynamic differences between mesocyclone cycles in tornadic and nontornadic supercells (e.g., Blanchard and Straka 1998; Wakimoto et al. 1998; Trapp 1999; Wakimoto and Cai 2000; Markowski 2002; Markowski et al. 2002; Beck et al. 2006), but some indicate that tornadic mesocyclone cycles might be longer (e.g., Lee et al. 2012).

Precise time observations from initial supercell development to tornado formation are not as well documented as times obtained from modeling results. Typically, 50–100 min (with longer times possible) elapse in idealized three-dimensional numerical simulations of supercells before they are mature enough, in tornado-supporting environments, to permit the development and support the maintenance of tornado-like vortices (e.g., Wicker and Wilhelmson 1995; Gaudet and Cotton 2006; Coffer and Parker 2017; Markowski 2020).

The interwoven relation between tornadic mesocyclones and tornadoes dictates that an individual tornado experiences its formative, maintenance and dissipative stages during one of its parent storm's low-level mesocyclone life cycles. With the typical tornado lasting ≤10 min (Edwards 2021) and a mesocyclone cycle period of roughly 40 min (e.g., Burgess et al. 1982; Lee et al. 2012), tornadoes can be inferred to take roughly 30 min to form from nascent mesocyclone processes (the typical tornadic mesocyclone cycle roughly ends with tornado dissipation, so that 40 min minus 10 min equals 30 min). Since long-lived supercell mesocyclone cycles can last more than two to four times longer than the cycle period of 40 min (80–160 min or longer; Bunkers et al. 2006a), storms with long-lasting mesocyclones potentially can support tornadoes lasting roughly 50 min (e.g., 80 min mesocyclone duration, minus 30 min for a tornado to form), with an upper duration bound of perhaps 130 min.

Additionally, a few well-documented tornadoes have lasted >150 min, as well as a few for >180 min. Examples of 1979–2018 tornadoes lasting >150 min include: 154 min (21 November 1992, Mississippi); 155 min (27 April 2011, Alabama); 160 min (02 June 1990, Illinois); 164 min (24 April 2010, Louisiana); 165 min (15 May 1980, Texas); 173 min (27 April 2011, Mississippi); 185 min (13 March 1990, Nebraska/South Dakota); and 195 min (07 June 1984, Missouri/Iowa). The average duration of these eight events is 168.9 min. Recently, there was an extremely long-lived and long-track tornado on 10 December 2021 that traversed 165.7 mi across Tennessee and Kentucky in 178 min (NWS 2022).

The PL choices (similar to those used in previous studies, Table 1) used to define long-track tornadoes, such as, 20, 25, 30, 40, 50, 60, 90, 100, and 150 mi (32.2, 40.2, 48.3, 64.4, 80.5, 96.6, 144.8, 160.9, and 241.4 km), are numerically convenient, but lack physical justification. A better range of PLs that can be used to define long-track tornadoes can be approximated simply by using some of the times above for long-lived mesocyclone cycles, incremented storm translation speeds ranging from 10, 20, …, 70 mph (4.5, 8.9, …, 31.3 m s^{-1}) and incremented PDs of 50, 100, 130, 150, and 180 min (Table 2). Large PL ranges are possible for these storm speeds and PDs, spanning 8.3–151.7 mi, up to 210 mi (13.4–244.1 km, up to 338.0 km). Using a tornado forward speed of 35 mph (15.6 m s^{-1}), which is roughly 50% of the maximum and 16.7% faster than the approximate average forward speed (30 mph or 13.4 m s^{-1}), and a PD range of 50–150 min (up to 180 min), gives a PL range of 29.2–87.5 mi [up to 105 mi; 47–140.8 km (up to 169 km)], or roughly 30–90 mi (48.3–144.8 km).

Based on distances from the 35-mph (15.6-m s^{-1}) tornado forward-speed value (Table 2, bottom row), a PL threshold of 30 mi (48.3 km) can be approximated to separate short-track tornadoes (effectively including both short- and intermediate-track tornadoes as defined by K78) from long-track tornadoes. Using tornado durations of 50, 100 and 150 min, and a 35-mph (15.6-m s^{-1}) tornado forward speed, PL subdivisions for long-track tornado PLs can be approximated herein as: long (L), [30, 60) mi or [48.3, 96.6 km); very long (V), [60, 90) mi or [96.6, 144.8 km); and extremely long (X), PL ≥90 mi or 144.8 km, which are roughly 1%, 0.1% and 0.03% of all tornadoes of any PL (Table 3) Short-track tornadoes (S) are approximated as having PL ≤30 mi (48.3 km).

Table 2: Possible path lengths (PLs) in mi (km) calculated from given translation speed in mph (m s^{-1}) and given path duration (PD; min).

	50 min	100 min	130 min	150 min	180 min
10 mph (4.5 m s^{-1})	8.3 (13.4)	16.7 (26.8)	21.7 (34.9)	25 (40.2)	30 (48.3)
20 mph (8.9 m s^{-1})	16.7 (26.8)	33.3 (53.6)	43.3 (69.7)	50 (80.5)	60 (96.6)
30 mph (13.4 m s^{-1})	25 (40.2)	50 (80.5)	65 (104.6)	75 (120.7)	90 (144.8)
40 mph (17.9 m s^{-1})	33.3 (53.6)	66.7 (107.3)	86.7 (139.5)	100 (160.9)	120 (193.1)
50 mph (22.4 m s^{-1})	41.7 (67.1)	83.3 (134.1)	108.3 (174.4)	125 (201.2)	150 (241.4)
60 mph (26.8 m s^{-1})	50 (80.5)	100 (160.9)	130 (209.2)	150 (241.4)	180 (289.7)
70 mph (31.3 m s^{-1})	58.3 (93.9)	116.7 (187.8)	151.7 (244.1)	175 (281.6)	210 (338.0)
35 mph (15.6 m s^{-1})	29.2 (47.0)	58.3 (93.9)	75.8 (122.0)	87.5 (140.8)	105 (169.0)

Table 3: Path length (PL) categories as defined in this study based on length in mi or km, number of 1979–2018 tornadoes in each PL category and percent (perc.) of all 1979–2018 tornadoes.

	PL mi (km)	Number	Percent
ALL	all	44 038	100
S	<30 mi or 48.3 km	43 605	99
LVX	≥30 mi or 48.3 km	433	0.98
L	[30–60) mi or [48.3–96.6) km	367	0.83
V	[60–90) mi or [96.6–144.8) km	52	0.12
X	≥90 mi or 144.8 km	14	0.03

Table 4: Possible path durations (PDs; min) calculated from given translation speed in mph (m s^{-1}) and given path length (PL) in mi (km).

	30 mi (48.3 km)	60 mi (96.6 km)	90 mi (144.8 km)
10 mph (4.5 m s^{-1})	180	360	540
20 mph (8.9 m s^{-1})	90	180	270
30 mph (13.4 m s^{1})	60	120	180
40 mph (17.9 m s^{-1})	45	90	135
50 mph (22.4 m s^{-1})	36	72	108
60 mph (26.8 m s^{-1})	30	60	90
70 mph (31.3 m s^{-1})	25.7	51.4	77.1
35 mph (15.6 m s–1)	51.5	102.9	154.3

The ALL PL category in this paper includes all of the tornadoes with PL >0 mi (0 km) in the database, except those filtered. The 30 mi (48.3 km) threshold is consistent with PL4 defined by FP73 as 32 mi (51.5 km) and used by K78 for long-track tornadoes.

Using various forward speeds for tornadoes of 10–70 mph (4.5–31.3 m s^{-1}), along with the PL subdivisions defined in Table 3, several possibilities for PD stratification can be estimated. By choosing a fast forward-translation speed of 60 mph (26.8 m s^{-1}), lower thresholds for PD stratification can be approximated as 30, 60 and 90 min, which permits rough categorizations for short-duration PD <30 min; long-duration [30, 60) min; very long-duration [60, 90) min; and extremely long-duration tornadoes PD ≥90 min tornadoes (Table 4). These can be compared to French and Kingfield (2019), who provided documentation of radar observations of 36 tornadoes with PD ≥20 min from 2012–2016, which had ranges of 20–78 min, with a median of 30 min and mean of 37 min (with uncertain representativeness). Translation speeds for the vast majority of tornadoes, parent-storm modes (supercell, QLCS, MCV) and associated mesocyclone durations in this 40-y study were unknown, and precluded a comprehensive study of tornado PD for this climatology.

4. Results and discussion

The total number of tornadoes, separated into 5-mi (8-km) PL bins (Fig. 1), shows that the percentage of the total number of tornadoes with PL ≥20, 25, 30, 40, 50, 60, 90, 100, and 150 mi (32.2, 40.2, 48.3, 64.4, 80.5, 96.6, 144.8, 160.9, and 241.4 km)—some of which have been used stratify long-track from short-track tornadoes—correspond to 2.4, 1.5, 0.98, 0.48, 0.25, 0.15, 0.032, 0.027, and 0.0023% of all tornadoes, respectively, in the United States from 1979–2018. The distribution of 24-h tornadoes across the bins was fairly smooth across the 5–90 mi (8.0–144.8 km) bins, and for nighttime was smooth across the 5–60 mi (8.0–96.6 km) bins. The more sporadic distribution at larger PLs reflected their smaller sample sizes. The daytime distribution of tornadoes was similar to that of 24 h.

The geographical distribution of long-track tornadoes can be seen in a track map using L, V, and X path length categorizations based on reported PLs and tracks determined from available latitude and longitude (similar to SPC's SVRPLOT program; Fig. 2). Unfortunately, PL distances determined from latitude and longitude and the reported PL distances were not always consistent (e.g., the X category 1981 eastern Iowa tornado had a track that appears to have length similar to an L rather than an X tornado). Furthermore, the use of beginning and ending points does not account for cycloidal or curved tracks. Thus, this map should be interpreted as an illustration of the general locations of long-track tornadoes, not exact tracks and/or path lengths. All long-track tornadoes occurred in the states east of the Rocky Mountains, except for two in Arizona.

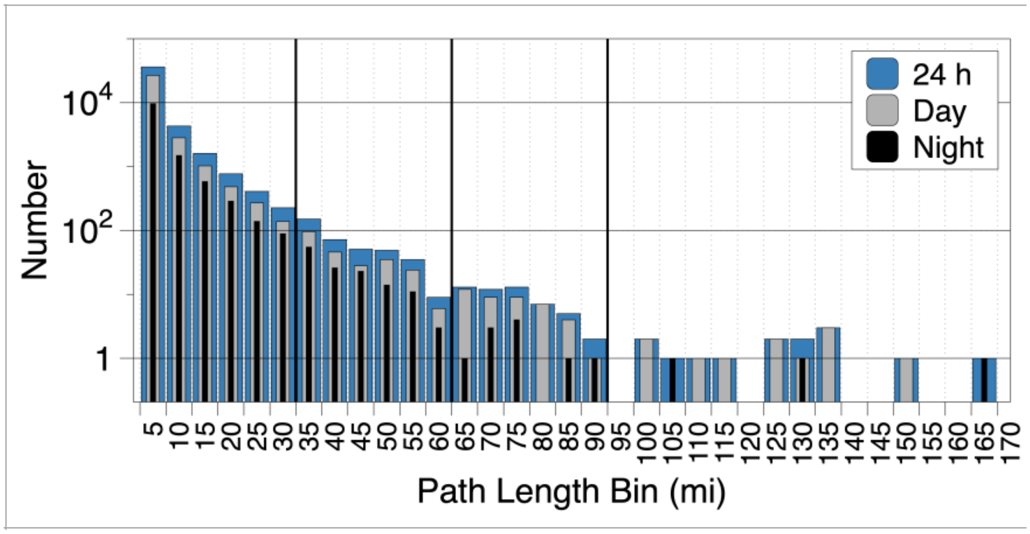

Figure 1: Log-linear bar chart of number tornadoes versus 5-mi (8-km) PL bin, (0–5), [5–10), [10–15), … [165–170) mi or (0–8.0), [8.0–16.1), [16.1– 24.1), ..., [265.5–273.6) km. Vertical bar colors denote numbers for 24-h (blue), day (grey) and night (black) tornadoes. Bold vertical lines demarcate 30, 60, and 90 mi or 48.3, 96.6 and 144.8 km.

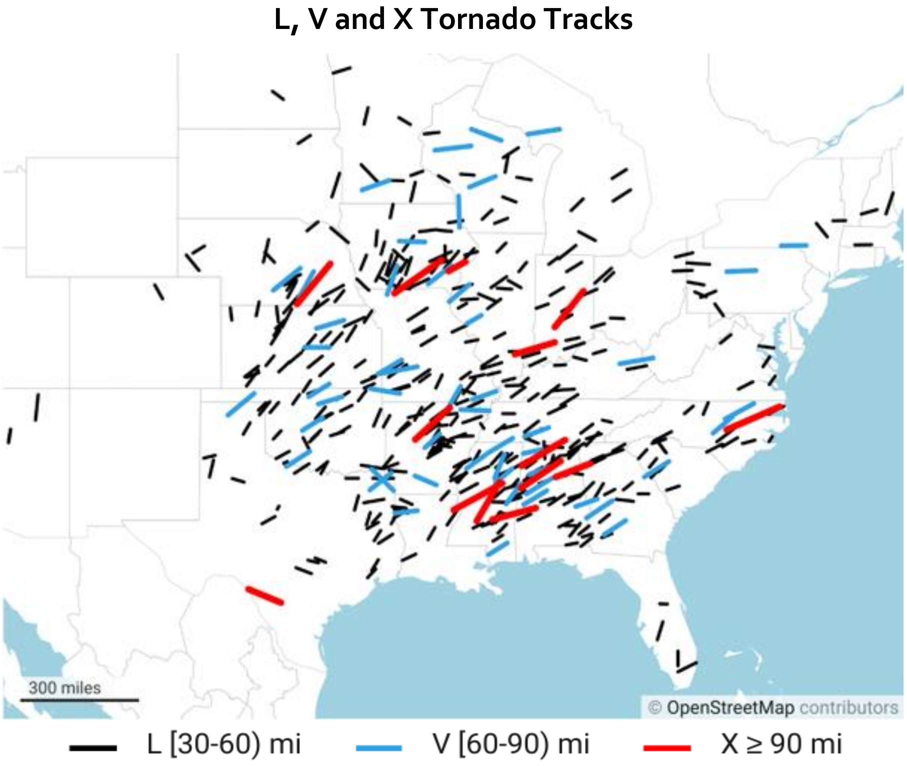

Figure 2: Map of tornado tracks for the tornado PL categories, L [30–60) mi or [48.3–96.6) km in black; V [60–90] mi or [96.6–144.8) km in blue and X ≥90 mi or 144.8 km in red. The categories were determined using the PLs and the lines were plotted using those entries with starting and ending latitude and longitude values from the dataset. All LVX cases from the dataset are plotted except two L cases that had identical beginning and ending points in the dataset.

Historically, the average annual number of ALL and S tornadoes in the database has increased for both 24 h and night (Fig. 3a, b), due in part to enhanced detection and greater public awareness of tornadoes (e.g., B04; Verbout et al. 2006). In contrast, the yearly number of LVX, L, V, and X tornadoes was approximately constant over the years for 24 h and night (Fig. 3a, b; nighttime LVX and L had slight increases). Interannual variability can be seen for all tornado PLs, most notably in 2011. In addition, the annual numbers of LVX, L, V, and X tornadoes typically were more numerous from 1950 to the mid-1970s (not shown) than from 1979–2018, perhaps related to the early inclusion of "skipping" tornado tracks that are rarely included in more modern reports (McCarthy and Schaefer 2004). There were 12 tornadoes with PL ≥150 mi (241.4 km) and four with PL ≥200 mi (321.9 km) between 1950–2018. From 1979–2018, only one tornado had PL ≥150 mi (241.4 km), and none had PL ≥200 mi (321.9 km).

Using the SPC dataset, the year with the largest peak frequency for LVX, L, V, and X tornadoes for 24 h is 2011, by far (Fig. 3a). The 2011 24-h LVX peak was ≈50% greater than the next highest year (2008; at night, 1982, 2006 and 2011 each had 10 LVX tornadoes). Also, April 2011 had a record number of 757 tornadoes for April ("around 758", Knupp et al. 2014). A record number of deaths and injuries for any month occurred in April 2011 (NCEI 2011) from "several significant, multi-day tornado outbreaks…" (NCEI 2011). These included 178 tornadoes from 14–16 April 2011 and an outbreak record of "~350" tornadoes from 25–28 April 2011 (Knupp et al. 2014; 343, Chasteen and Koch 2021). The effect of tornado outbreaks in 2011, especially in April 2011, on the monthly tornado climatology is discussed in section 4e.

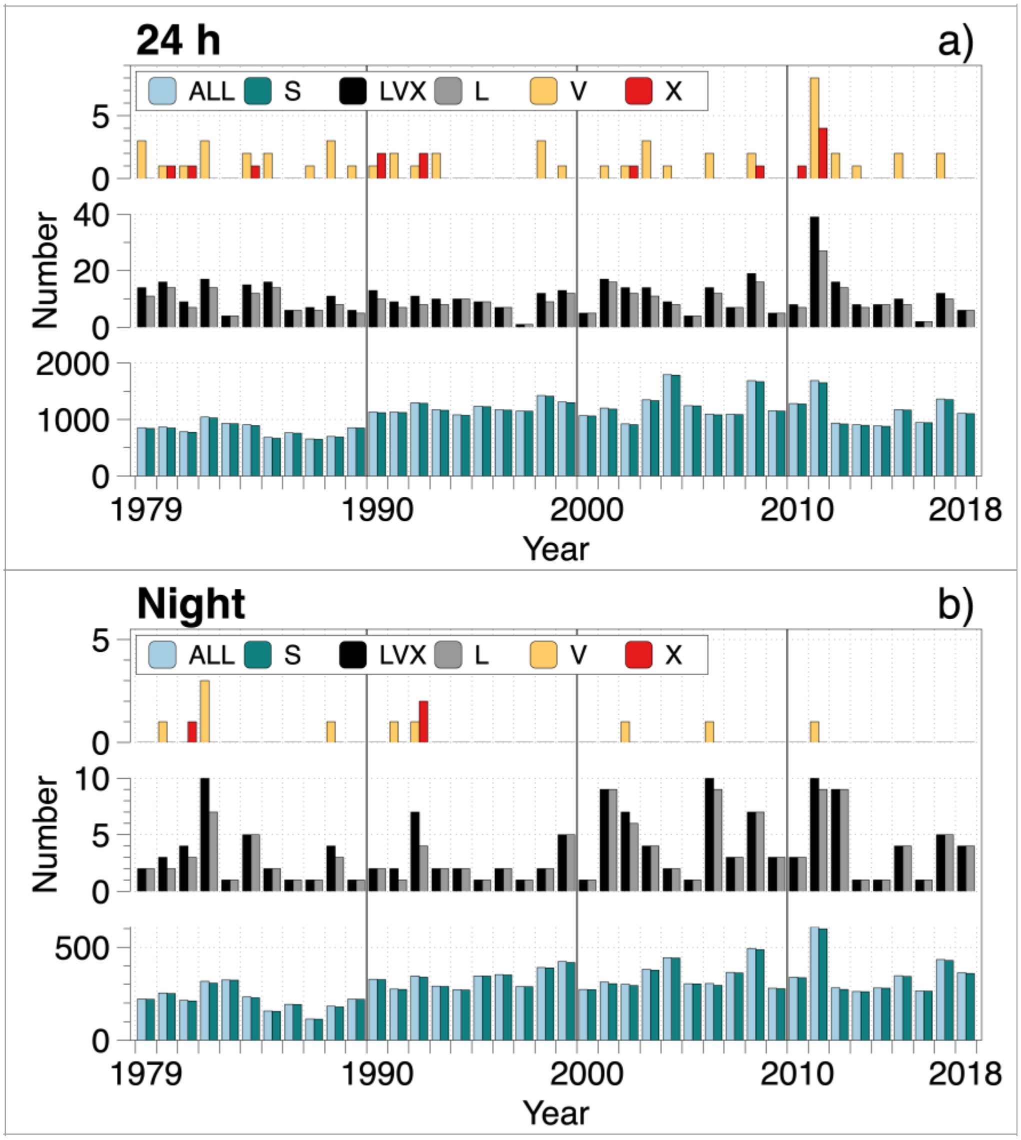

Figure 3: Linear-linear bar charts of number of tornadoes versus year for the ALL, S, LVX, L, V, and X tornado PL categories for a) 24 h and b) night. Note the different scales on the vertical axes.

The disproportionate number of deaths and injuries caused by long-track tornadoes was significant (Fig. 4). Although 24-h L, V, and X tornadoes made up 0.98% of ALL tornadoes (Table 3; Fig. 4a), these accounted for 32.3% of the total deaths and injuries with ALL tornadoes (Fig. 4c). At night, 21.5% of the total deaths and injuries (Fig. 4h) were associated with L, V, and X tornadoes, which made up 1.17% of ALL nighttime tornadoes (Fig. 4f, g). Normalizing the number of deaths and injuries by the number of tornadoes (Fig. 4d, i) shows that L, V, and X tornadoes were associated with one to two orders of magnitude more deaths and injuries per tornado than S tornadoes for 24 h and night, with the maximum for X tornadoes. To remove the area dependence of the long PLs of long-track tornadoes, the values of the deaths and injuries, divided by the number of tornadoes, then were divided by the sum of all the PLs of all the tornadoes in each PL category (Fig. 4e, j). This shows the number of total deaths and injuries per tornado per PL mile was at least two orders of magnitude larger for L, V, and X tornadoes than for S tornadoes. They also caused over 99.9% of the total deaths and injuries per tornado per PL mile for both 24 h and nighttime. Though they were few in number, long-track tornadoes have had a devastating impact on human life.

Finally, D06 has noted that tornado outbreaks were associated with larger numbers of long-track tornadoes. The number of tornadoes which constitutes an “outbreak” has been discussed, for example, by Edwards et al. (2004), and in more detail by D06 and Shafer and Doswell (2010). Edwards et al. (2004) suggested increasing the number from five to reflect the enhanced reporting of tornadoes in recent years (though their intent was not to assign a set number to define an outbreak). On 259 days, at least one LVX occurred. Of those 259 days, the total number of tornadoes was greater than 5, 10, 20, 30, or 40 (i.e., outbreak days) on 221 (85.3%), 192 (74.1%), 122 (47.1%), 76 (29.3%), and 53 (20.5%) days, respectively. These percentages further support the association between the occurrence of long-track tornado days and outbreak days (D06).

a. F/EF scale

Most tornadoes have damage rating ≤F/EF1 for 24 h (87.1%; Fig. 5a). There were progressively fewer ALL tornadoes for each increase in F/EF scale. The typical F/EF scale associated with ALL and S tornadoes was less than that associated with LVX, L, V, and X tornadoes, consistent with K78, B04, G07 and E14. In addition, E14 found that any given EF category had a wide range of PLs, as well as PWs, but there was a “clear relationship between EF category and path length, as well as between EF category and path width” (e.g., most tornadoes with PL >18.08 mi or 29.1 km were associated with ≥F/EF3 damage). Similarly, herein, the majority of 24-h ALL and S tornadoes were F/EF0, while LVX, L, and V tornadoes had maxima at E/EF3 and X tornadoes had maxima at E/EF4. Only a small number of long-track tornadoes were rated F/EF0–1. Additionally, 32.9% of F/EF4–5 tornadoes were LVX tornadoes, consistent with previous results (e.g., B04 and E14).

Unsurprisingly, fewer nighttime tornadoes occurred than the 24-h number, regardless of PL or damage rating. As with 24 h, most nighttime tornadoes were rated ≤F/EF1 (82.9%; Fig. 5b). The nighttime patterns for ALL and S tornadoes were similar to 24 h, but the LVX tornadoes were distributed more sporadically over the F/EF scale. There were very few nighttime V and X tornadoes and only three nighttime F/EF5 tornadoes (one S and two L tornadoes), including the 36-mi, long-track Barneveld, WI tornado at 2341 CST 7 June 1984 (0541 UTC 8 June 1984).

A box-and-whisker plot of the distributions of 24-h PLs for each F/EF-scale rating (Fig. 5c) shows the variability of PL distribution with damage rating, and also supports the association of longer PLs with larger ratings, as shown by B04 for PLs >25 mi (40.2 km) rated F/EF 4–5. The median (and mean) PL also increases with increasing rating. Additionally, the distributions were much less concentrated for the larger ratings, and were positively skewed for all ratings, except negatively skewed for relatively small-sample F/EF5 categories.

The current study period of 1979–2018 affords comparisons with K78, and the evaluation of whether the results relating PL and F/EF scale are extendable from K78’s 1950–1976 results. Path length data are grouped as in K78 to facilitate a comparison. The percent of tornadoes in each doubly grouped PL and E/EF category (Fig. 5d), indicates that categories PL0–1, PL4–5 and the total for all PLs, had the same pattern for K78 (grey bars) and the current years of study (red bars; labeled 7918). One difference is for intermediate PLs (PL2–3), where K78 showed the largest number of tornadoes was associated with F/EF2–3 ratings, while for the years of the current study, the largest number of tornadoes was associated with F/EF0–1 ratings.

In particular, the percentages of F/EF0–1 tornadoes were much larger (>20%) for PL0–1, PL2–3 and the total for all PLs for 1979–2018 than for the years of K78. This reflects the increase in F/EF0 tornado numbers with time (e.g., Verbout et al. 2006) and possibly in the mean of F/EF1 tornadoes since 2007 (EBC21). The percentages for the longest-track tornadoes (PL4–5) are remarkably similar for the two periods of study, with slightly more (6–8%) F/EF2–3 in this study. The general relationship of longer PLs to larger F/EF scale documented for 1950–1976 (K78) essentially holds for 1979–2018, though there were some differences for short and intermediate PLs. The results of the 26-y climatology of K78 may have been influenced by the large number of violent and/or long-track tornadoes from the 3–4 April 1974 outbreak, though this was not explored.

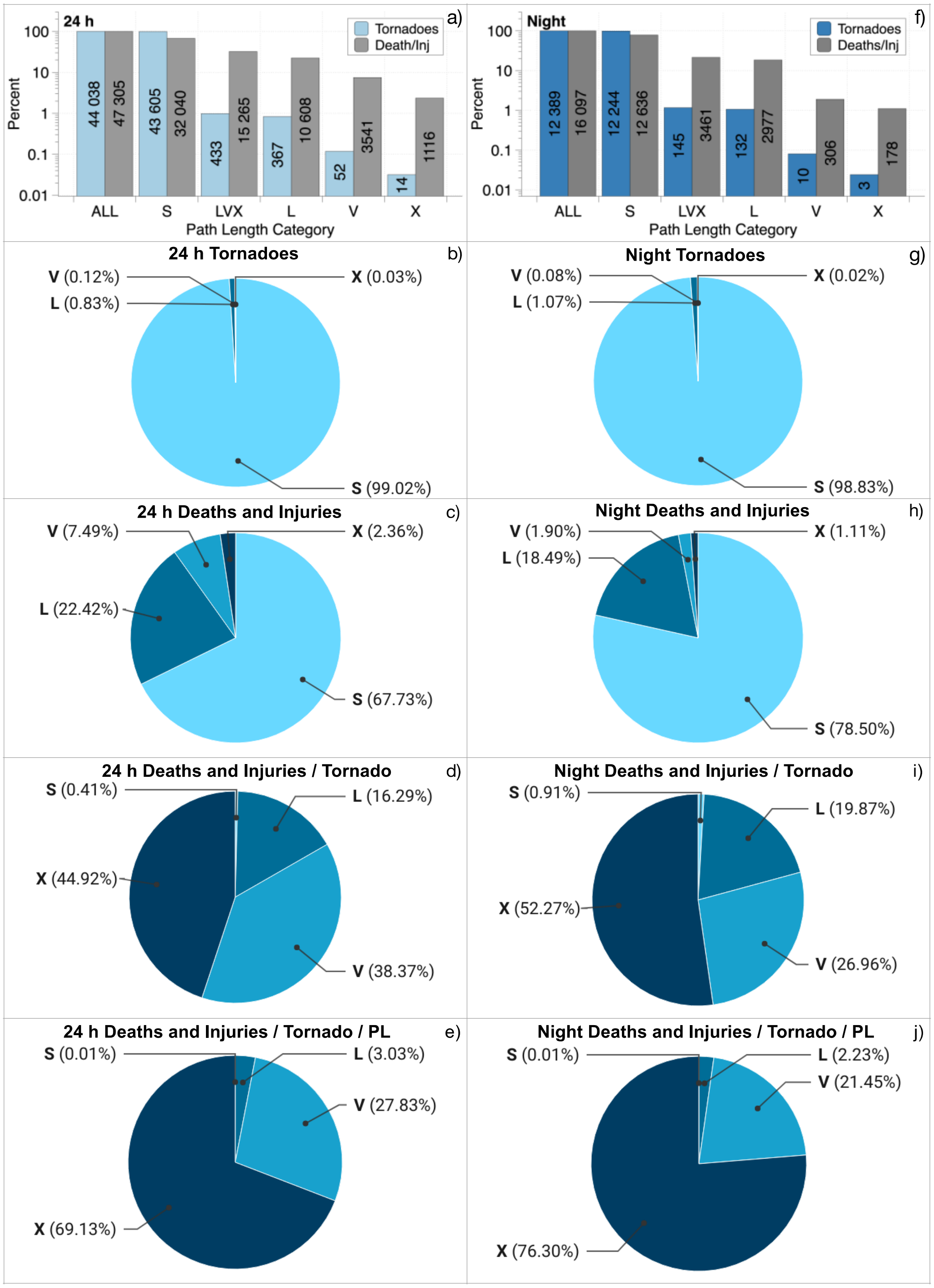

Figure 4: a) Log-linear bar chart of total number of 1979–2018 tornadoes in the United States in each of the ALL, S, LVX, L, V, and X tornado PL categories. Vertical bar colors denote totals for 24-h tornadoes (blue; numeric labels within bars are percent of all 1979–2018 tornadoes) and 24-h deaths and injuries (grey; numeric labels within bars are percent of all 1979–2018 deaths and injuries); b) Pie chart depicting the percent of the 24-h total tornadoes for the S (light blue), L (blue), V (dark blue), and X (very dark blue) tornado PL categories; c) As in (b), but for 24-h deaths and injuries; d) As in (c), but for 24-h deaths and injuries normalized by the number of tornadoes (deaths and injuries/tornado); e) As in (d), but for 24-h deaths and injuries normalized by the number of tornadoes and the sum of the PLs of tornadoes in each PL category (deaths and injuries /tornado/PL); f)–j). As in (a)–(e), but for nighttime values.

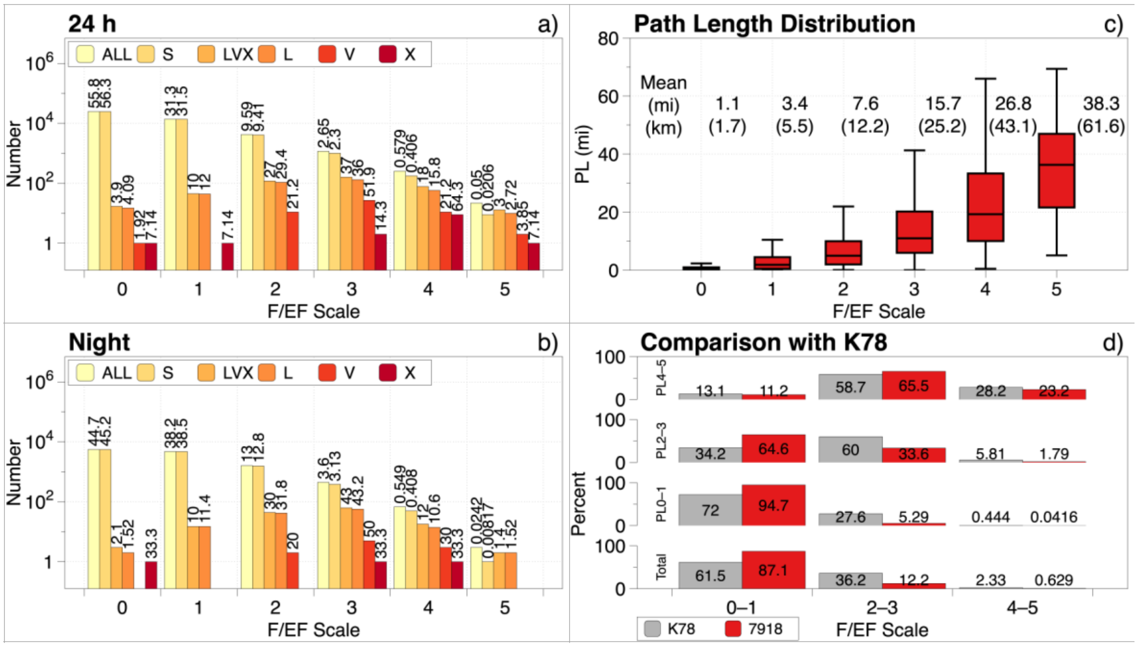

Figure 5: Log-linear bar charts of number of tornadoes versus F/EF-scale rating for the ALL, S, LVX, L, V, and X tornado PL categories for a) 24 h and b) night. Numeric labels are percent of the total number in a given PL category; c) Box-and-whisker plot of 24-h PL distributions for each F/EF-scale rating (outliers omitted). Tops and bottom of boxes represent 75th and 25th percentiles, respectively. Tops and bottoms of whiskers represent 90th and 10th percentiles, respectively. Middle line of the box is the median. Numeric labels indicate the mean PL in mi (km) for each F/EF-scale rating; d) Linear-linear bar chart of the percent of tornadoes versus F/EF-scale rating (grouped by two rating categories) for K78 (grey bars) and the current years of study (labeled 7918 to denote the years of the current study, 1979–2018; red bars) using the approximate PL categories of K78: PL0–1, 0–3.1 mi (0–5.0 km); PL2–3, 3.2–31 mi (5.1–50.0 km); and PL4–5, 32–315 mi (51.5–507 km). Numeric labels indicate the percent of the total in the PL category.

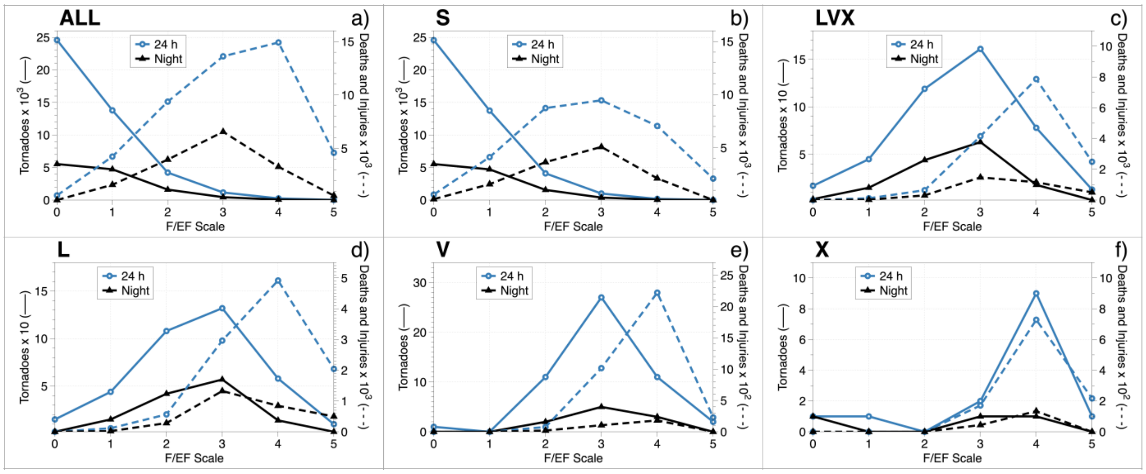

Figure 6: Line graphs of number of tornadoes (solid; left axis) and deaths and injuries (dashed; right axis) versus F/EF-scale rating for the a) ALL, b) S, c) LVX, d) L, e) V, and f) X tornado PL categories for 24 h (blue circles) and night (black triangles). Note the different scales on the vertical axes. *Click image to enlarge.*

As expected, the deaths and injuries for 24-h (Fig. 6a, b; blue lines) ALL and S tornadoes were greatest for larger F/EF ratings, even though the vast majority of tornadoes were rated F/EF0. The maximum nighttime (Fig. 6a, b; black lines) number of deaths and injuries for ALL and S tornadoes occurred with F/EF3 tornadoes, while the maximum frequency of nighttime ALL and S tornadoes was at F/EF0. S tornadoes had many fewer total deaths and injuries (Fig. 6b) than ALL (Fig. 6a). This supports the finding shown in Fig. 4c–f that a large contribution to the total number of deaths and injuries owes to LVX tornadoes, consistent with prior studies (e.g., G07). The largest number of deaths and injuries for 24-h LVX, L, V, and X tornadoes (Fig. 6c–f) were associated with F/EF4 tornadoes. The maximum nighttime deaths and injuries were associated with F/EF3 ratings for LVX and L (Fig. 6c, d) tornadoes, but with F/EF4 for V and X (Fig. 6e, f).

b. Geographical regions

Geographical regions (Table 5; Fig. 7) were defined as the Southeast (SE; 459 055 mi^2 or 1 188 947 km^2), Midwest (MW; which includes the Ohio River Valley; 554 818 mi^2 or 1 436 972 km^2), and Great Plains (GP; 645 969 mi^2 or 1 673 052 km^2), and comprise the entire areas of the individual states within them. (Surface areas of states used were not updated with values from the 2020 census since the study date ends at 2018). Because the area of the Great Plains is much larger than that of the Midwest or Southeast, any area-weighted values are reduced most for the Great Plains. While the definition of Great Plains used was similar to that in B03, this definition is not entirely consistent with other definitions, such as those used by K78, Taszarek et al. (2020) and Grams et al. (2012).

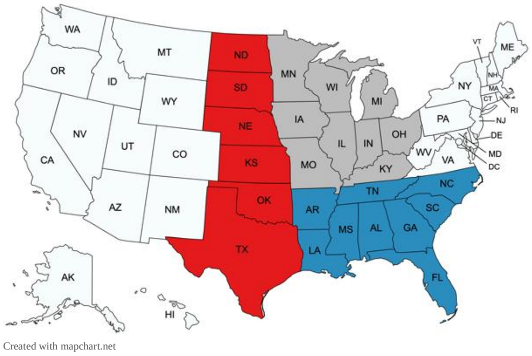

Figure 7: Map depicting the three geographic regions as defined for this study, Southeast (SE; blue), Midwest (MW; grey), and Great Plains (GP; red).

The number of tornadoes in each geographic region, for each PL category, is shown in Table 6 (annual number of tornadoes in parentheses). All but 21 (4.8%) of the LVX tornadoes occurred within the three geographic regions (Table 6). While the largest annual number of tornadoes occurred in the Great Plains, the largest annual number of LVX tornadoes occurred in the Southeast (consistent with K78). The region with the most area-normalized tornadoes, and with the longest average LVX PL (sum of all LVX PLs per region divided by the total number of tornadoes per region) is the Southeast, followed by the Midwest and Great Plains with 3.73, 2.31, and 1.75 LVX tornadoes per 10 000 mi^2 (25 900 km^2) and mean LVX PL = 46.6, 45.3, and 44.8 mi (75, 72.9, and 72.1 km), respectively.

There were more 24-h ALL PL tornadoes per 10 000 mi^2 (25 900 km^2) in the Southeast than in the Great Plains and Midwest (Fig. 8a). This difference between the Southeast, and the

Table 5: States included in each of the three geographic regions, as defined in the current study, and the total area of each region.

Southeast **459 055 mi^2 (1 188 947 km^2)**	**Midwest** **554 818 mi^2 (1 436 972 km^2)**	**Great Plains** **645 969 mi^2 (1 673 052 km^2)**
Alabama	Illinois	Kansas
Arkansas	Indiana	Nebraska
Florida	Iowa	North Dakota
Georgia	Kentucky	Oklahoma
Louisiana	Michigan	South Dakota
Mississippi	Minnesota	Texas
North Carolina	Missouri	
South Carolina	Ohio	
Tennessee	Wisconsin	

Table 6: Total tornadoes per geographic region, Southeast (SE), Midwest (MW), and Great Plains (GP), for the 40 y between 1979–2018 (annual number in parentheses) for the PL categories as defined in this study. "Three-Region Sum" is the sum of the numbers in the three geographic regions. For convenience, the total numbers for the 48 states from Table 3 are repeated here in the rightmost column.

	Southeast	Midwest	Great Plains	Three-Region Sum	Total 48 States
X	8 (0.2)	4 (0.1)	2 (0.05)	14 (0.35)	14 (0.35)
V	22 (0.6)	14 (0.4)	14 (0.4)	50 (1.25)	52 (1.3)
L	141 (3.5)	110 (2.8)	97 (2.4)	348 (8.7)	367(9.2)
LVX	171 (4.3)	128 (3.2)	113 (2.8)	412 (10.3)	433 (10.8)
S	11 917 (297.9)	10 436 (260.9)	15 022 (375.6)	37 375 (934.4)	43 605 (1090)
ALL	12 088 (302.2)	10 564 (264.1)	15 135 (378.4)	37 787 (944.7)	44 038 (1101)

Midwest and Great Plains, was even greater at night (Fig. 8b). Likewise, the maximum number of 24-h and night deaths and injuries per 10 000 mi^2 (25 900 km^2) was in the Southeast for all PLs (Fig. 8c, d), consistent with the largest regional number of tornadoes.

Maps of the number of tornadoes (Figs. 9–10) and deaths and injuries (Fig. 11) per 10 000 mi^2 (25 900 km^2) per year are shown, made non-dimensional by the maximum value for each classification. Though tornadoes occurred in every state, the maximum numbers of 24-h ALL and S tornadoes (Fig. 9a, b) occurred mainly in the Great Plains and Southeast states. At night, the frequency of ALL and S tornadoes shifted toward the Southeast (Fig. 9d, e). Long-track tornadoes generally occurred east of the Rocky Mountains into New England and Florida (Fig. 9c, f; Fig. 10), but the very few longest-track tornadoes (X) were concentrated mostly in Mississippi and Alabama, with single occurrences elsewhere (shading reflects area-weighted values; Fig. 10c, f; Fig. 2). Most of the nighttime long-track tornadoes occurred in the Southeast (Fig. 9f). Additionally, several nocturnal L, V, and X tornadoes occurred in the Midwest and southern Great Plains (Fig. 10d–f), but not in the Dakotas of the northern Great Plains. Interestingly, the night maximum value was in Mississippi for all PL categories.

The maximum annual, area-weighted numbers of deaths and injuries per unit area (normalized by the maximum value for each classification) for 24-h ALL tornadoes (Fig. 11a) were in the Southeast states (the Connecticut maximum is associated with a smaller number of tornadoes that caused a relatively high number of deaths and injuries, coupled with the small area). The 24-h maxima for S tornado related deaths and injuries (Fig. 11b) were similarly distributed. Additionally, the area-normalized LVX deaths and injuries maxima for 24-h periods (Fig. 11c) were mostly in the Southeast, though some appeared in the southern Great Plains. The nighttime ALL and S deaths and injuries maxima had an even stronger signal in the Southeast than the 24-h totals (Fig. 11d, e). The nighttime death and injury maxima for LVX tornadoes (Fig. 11f) were also the largest in the Southeast. A comparison of Fig. 11 to Fig. 9 shows the normalized numbers of death and injuries from LVX tornadoes in many states were the same order of magnitude as that of S tornadoes, even though the actual numbers of tornadoes were one order of magnitude smaller for LVX than for S. These figures summarily show that nocturnal tornadoes were particularly devastating in terms of deaths and injuries, especially in the Southeast.

Figure 12 shows the 24-h annual number of tornadoes per 10 000 mi^2 (25 900 km^2) in each geographic region versus F/EF-scale rating for each PL category. The 24-h ALL and S tornadoes were most likely to be rated F/EF0, and to be in the Great Plains (Fig. 12a). The maximum number of ALL and S F/EF1 tornadoes occurred in the Southeast. For LVX, L and V (X) tornadoes, the predominant damage rating was F/EF3 (F/EF4). Damage rating of tornadoes increased with increasing PL (Fig. 5), especially in the Southeast, which is similar to K78. At night (Fig. 12b), the maximum numbers of ALL and S tornadoes were in the Southeast for F/EF1–5 ratings, with most of these rated F/EF0–1. The damage ratings of the five V and two X nighttime tornadoes were largely F/EF3–4.

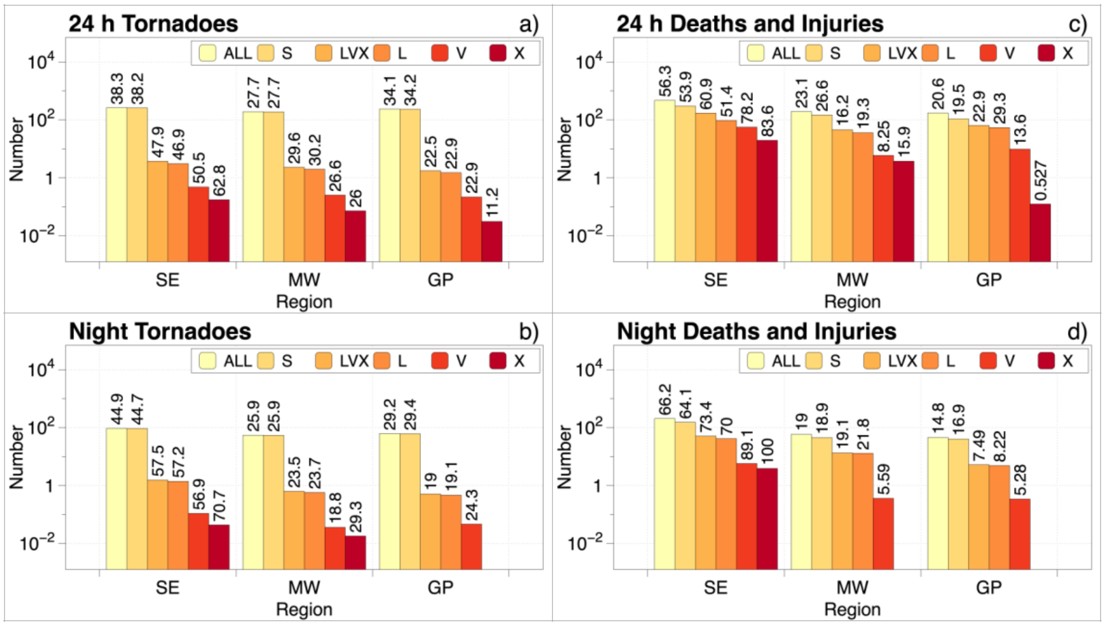

Figure 8: Log-linear bar charts of number of tornadoes per 10 000 mi^2 (25 900 km^2; left) and deaths and injuries per 10 000 mi^2 (25 900 km^2; right) versus geographic region, Southeast (SE), Midwest (MW) and Great Plains (GP) for the ALL, S, LVX, L, V, and X tornado PL categories for 24 h (top) and night (bottom). Numeric labels are percent of the total in all three regions for a given PL category.

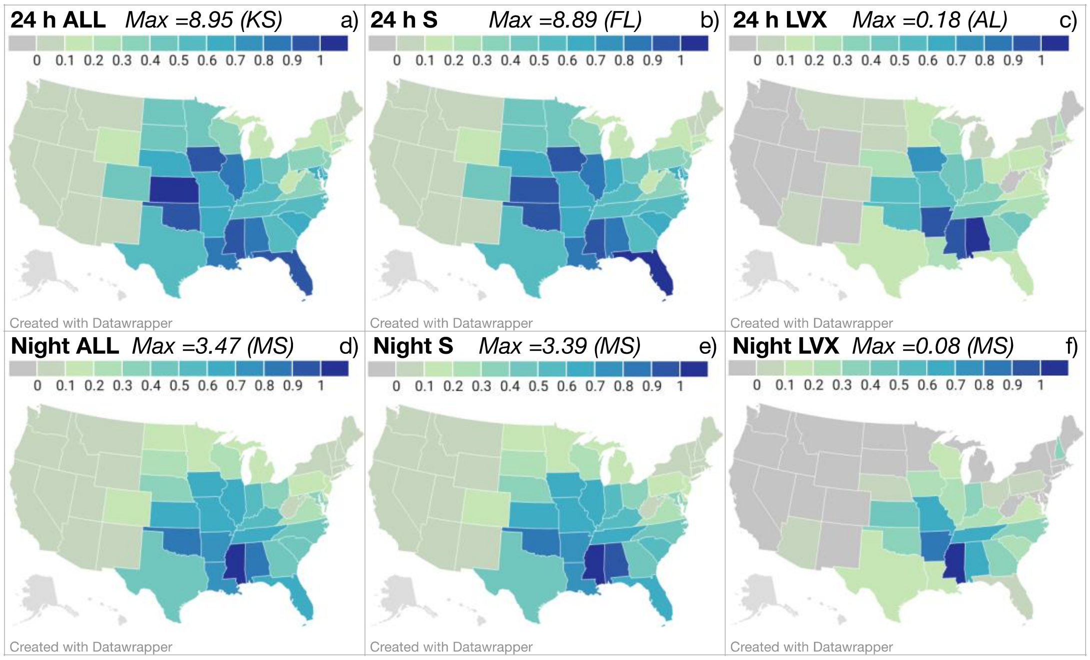

Figure 9: Maps of annual tornado number per 10 000 mi^2 (25 900 km^2) per state, made non-dimensional by dividing by the value for the state with the maximum annual area-weighted number of tornadoes (this maximum value is displayed in top center of each panel along with the classification's maximum state). Dimensionless values are given for the state in which tornadoes began for the ALL (left), S (middle) and LVX (right) tornado PL categories for 24 h (top) and night (bottom). States with grey shading had zero occurrences for the classification. Hawaii, Alaska and the District of Columbia were excluded.

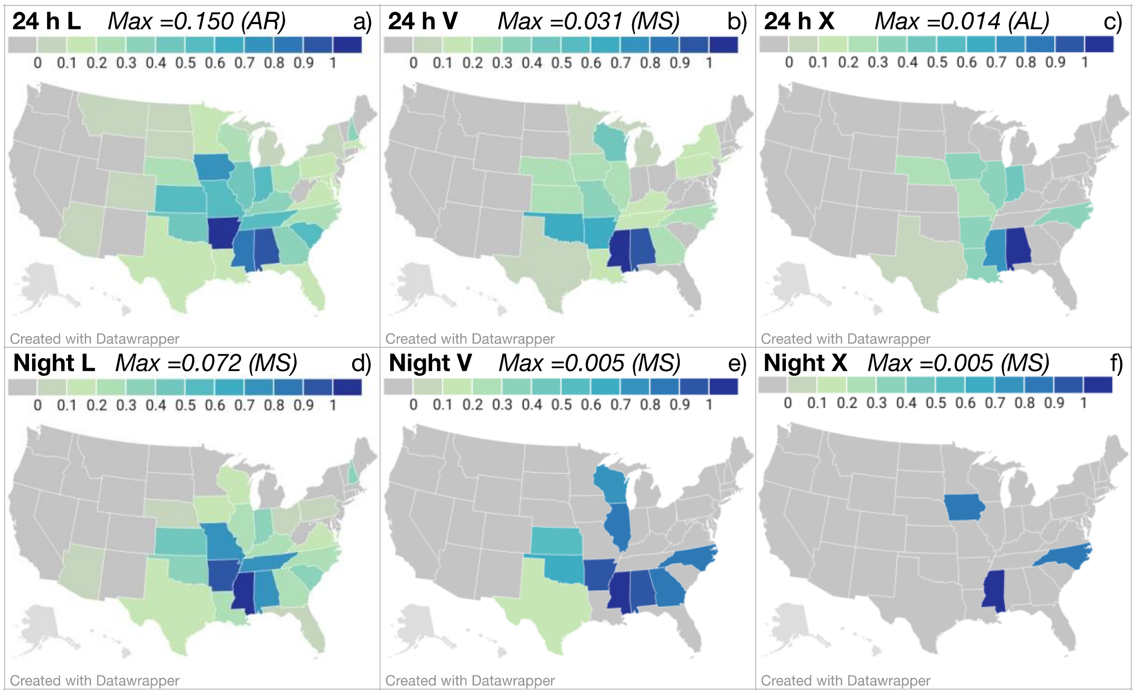

Figure 10: As in Fig. 9, but for the non-dimensional number of tornadoes for the L (left), V (middle) and X (right) tornado PL categories for 24 h (top) and night (bottom).

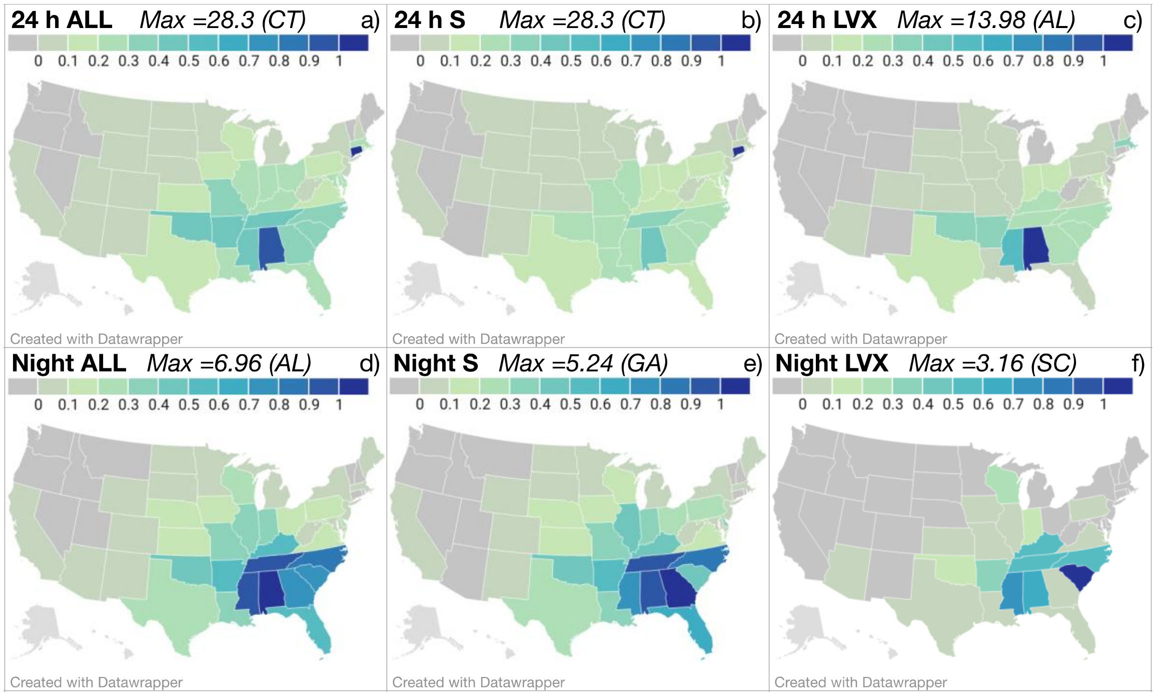

Figure 11: As in Fig. 9, but for the non-dimensional number of deaths and injuries for the ALL (left), S (middle) and LVX (right) tornado PL categories for 24 h (top) and night (bottom).

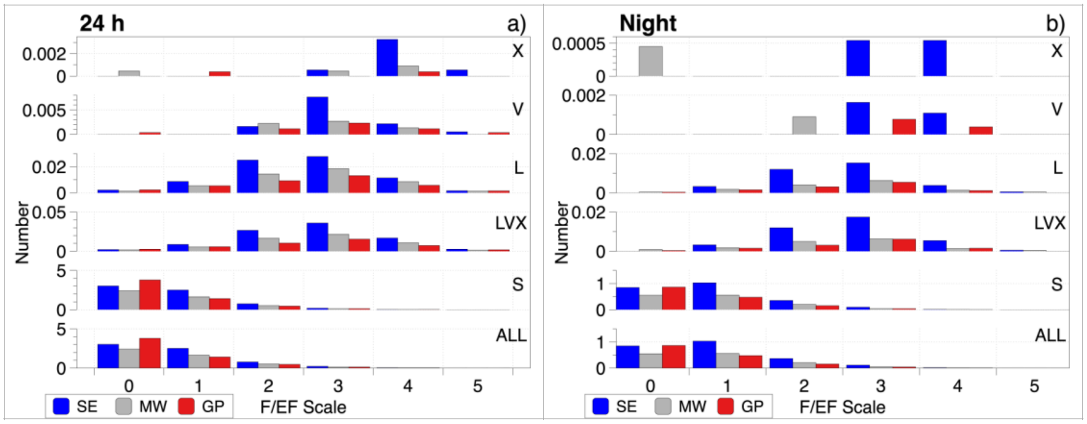

Figure 12: Linear-linear bar charts of annual number of tornadoes per 10 000 mi^2 (25 900 km^2) versus F/EF-scale rating for the ALL, S, LVX, L, V, and X tornado PL categories for each geographic region, Southeast (SE; blue), Midwest (MW; grey) and Great Plains (GP; red). a) 24 h and b) night. Note the different scales on the vertical axes.

Regional comparisons with K78 (not area-weighted) show the percent of F/EF0–1 tornadoes was at least 24% greater in the current study than in K78 (Table 7) for all regions. Concomitantly, the percent of F/EF2–3 tornadoes was 2–3 times less for the current study than in K78, with the largest percent in the Southeast region for both studies; however, the largest percent of F/EF0–1 tornadoes was in the Great Plains for both studies. The K78 percent of F/EF4–5 tornadoes was tied between the Southeast and Midwest, but was in the Midwest for this study. Interestingly, higher-rated tornadoes were most likely in regions outside the Great Plains relative to lower-rated tornadoes, in both studies.

c. Mean path width

The annual mean unadjusted tornado PW (original PW reported in the SPC database; Fig. 13a; yd; light blue) and annual mean PL (Fig. 13a; mi; grey) were found to increase with time, which EBC21 found especially to be associated with the EF damage-scale rating era (starting in 2007). However, the annual mean PL decreased in the last decade (Fig. 13a; grey), consistent with EBC21 (their Fig. 11a; though they do not emphasize this point). Path widths were adjusted for three eras, 1979–1994, 1995–2006, and 2007–2018 (Fig. 13a; blue; justification for these eras was described in section 2). Hereafter, the PWs used and described will be the adjusted PWs for these three eras. The correlation of tornado PW with tornado PL (Fig. 13b) was weak, 0.227, having some increase in PW with increasing PL. The percent of S (0.12%) and LVX (3%) tornadoes with PW >1500 yd (1371.6 m) indicates that very wide tornado PWs are associated with longer tornado PLs, consistent with B04 and E14 (Fig. 13b, c). The median PW is about ten times larger for LVX than for S tornadoes (Fig. 13c).

The mean PW (blue) and the mean PL (grey) increased as the F/EF scale increased for ALL tornadoes (mean for each F/EF-scale rating; Fig. 14a) and the mean PW increased with F/EF scale for LVX tornadoes (Fig. 14b). The mean PL was almost independent of F/EF scale for LVX tornadoes (Fig. 14b). Interestingly, the mean PL was shorter for F/EF1 tornadoes than for F/EF0 tornadoes. Brooks (2004) investigated the statistical associations of tornado damage rating, PW and PL, and found that longer-PL tornadoes were generally wider with higher F-scale damage

Table 7: Percent of total tornadoes in each geographic region, Southeast (SE), Midwest (MW) and Great Plains (GP), for each F/EF-scale rating (grouped by two rating categories) for K78 and the current study (labeled as 7918 to denote the years of the current study, 1979–2018). Note that these regions were defined somewhat differently in K78 than in the current study.

	F/EF0–1		F/EF2–3		F/EF4–5	
	K78	7918	K78	7918	K78	7918
SE	49.7	84.1	47	15.2	3.3	0.71
MW	57.7	85.3	39	14.0	3.3	0.77
GP	64.7	88.9	33.7	10.5	1.6	0.63

ratings. However, the association was not strong enough to confidently state wider- or longer-path tornadoes were associated with greater F-scale ratings. Additionally, E14 generally found larger PW and EF damage-scale ratings with longer-PL tornadoes, and that the association between PL and PW was strongest for the widest tornadoes. Agee and Childs (2014) also found higher ratings with wider tornadoes, especially in the later period of their climatology.

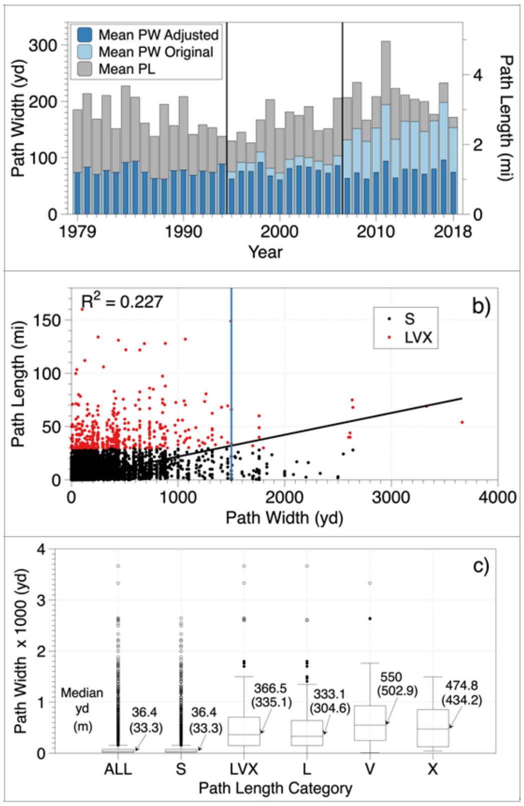

Figure 13: a) Linear-linear bar chart depicting annual mean adjusted path width (PW; yd; blue), the annual mean unadjusted original PW (light blue), and annual mean path length (PL; mi; grey) versus year. b) Scatter plot of PL (mi) versus PW (yd; adjusted for three eras), for the S (black dots) and LVX (red dots) tornado PL categories. Linear fit is shown in bold black and the correlation is 0.227. The blue line denotes PW = 1500 yd (1371.6 m). c) Box-and-whisker plot of PW distributions (adjusted for three eras) for each PL category. Tops and bottom of boxes represent 75th and 25th percentiles, respectively. Tops and bottoms of whiskers represent 90th and 10th percentiles, respectively. Middle line of the box is the median. Numeric labels indicate the median PW in yd (m). *Click image to enlarge*.

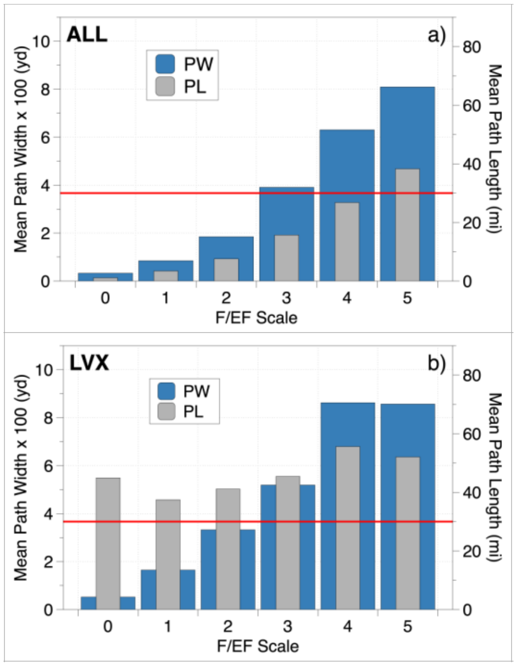

Figure 14: Log-linear bar chart of mean PW (yd; blue) and mean PL (mi; grey) for each F/EF-scale rating for the a) ALL and b) LVX tornado PL categories versus F/EF-scale rating. Red line denotes PL = 30 mi (48.3 km).

The states with the largest 1979–2018 mean PWs (Fig. 15a) and mean PLs (Fig. 15c) for ALL tornadoes stretched from Oklahoma toward the east-southeast through Georgia (mean state PL and PW values were normalized by the maximum mean state value for each of PW and PL). The large mean PW value in Rhode Island (Fig. 15a) was due to the small number (10) of total tornadoes, many of which had wide paths. Mean PW and PL values for LVX tornadoes were generally larger from Oklahoma northward to Minnesota and from Louisiana eastward to Georgia (Fig. 15b, d). Anomalies in Pennsylvania and New Hampshire occurred on three dates with a total of five LVX for Pennsylvania and two dates with single LVX events for New Hampshire.

d. Destruction Potential Index and area scale

Doswell et al. (2006) used the Destruction Potential Index (DPI; Thompson and Vescio 1998), defined as the sum over all tornadoes in an outbreak, of the product of (F scale+1), PL and PW. The DPI is limited by the use of the peak EF tornado rating, as the rating is not generally applicable to the entire tornado path, especially for more violent tornadoes (e.g., Marshall 2002; Burgess et al. 2014). Other limitations of the DPI include the subjectivity of the F/EF scale (e.g., Doswell and Burgess 1988; Edwards 2003; Edwards et al. 2013) and that if tornadoes over open country do not damage structures, they are given a low weight. The concept of "Fujita miles" (Fuhrmann et al. 2014), which is not used here, has tornado PL and peak EF rating combined, but also suffers from the same limitations as DPI.

The dependence of the DPI on F/EF scale can be avoided by using the area scale (A-scale = PL × PW; F71; Thompson and Vescio 1998). Unsurprisingly, the general patterns found for the mean DPI and mean A-scale were similar (mean was calculated per tornado for each PL category, for each geographic region; Fig. 16). The DPI (A-scale) values were about 1–2 (2–3) orders of magnitude larger for the LVX, L, V, and X tornadoes, than for the S and ALL tornadoes. The largest values of the DPI and A-scale in the Southeast were associated with V and X tornadoes, regardless of the time of day. The DPI and A-scale in both the Great Plains and Midwest, were largest for 24-h and nighttime, V tornadoes. These general DPI and A-scale findings for short- and long-track tornadoes are consistent with G07.

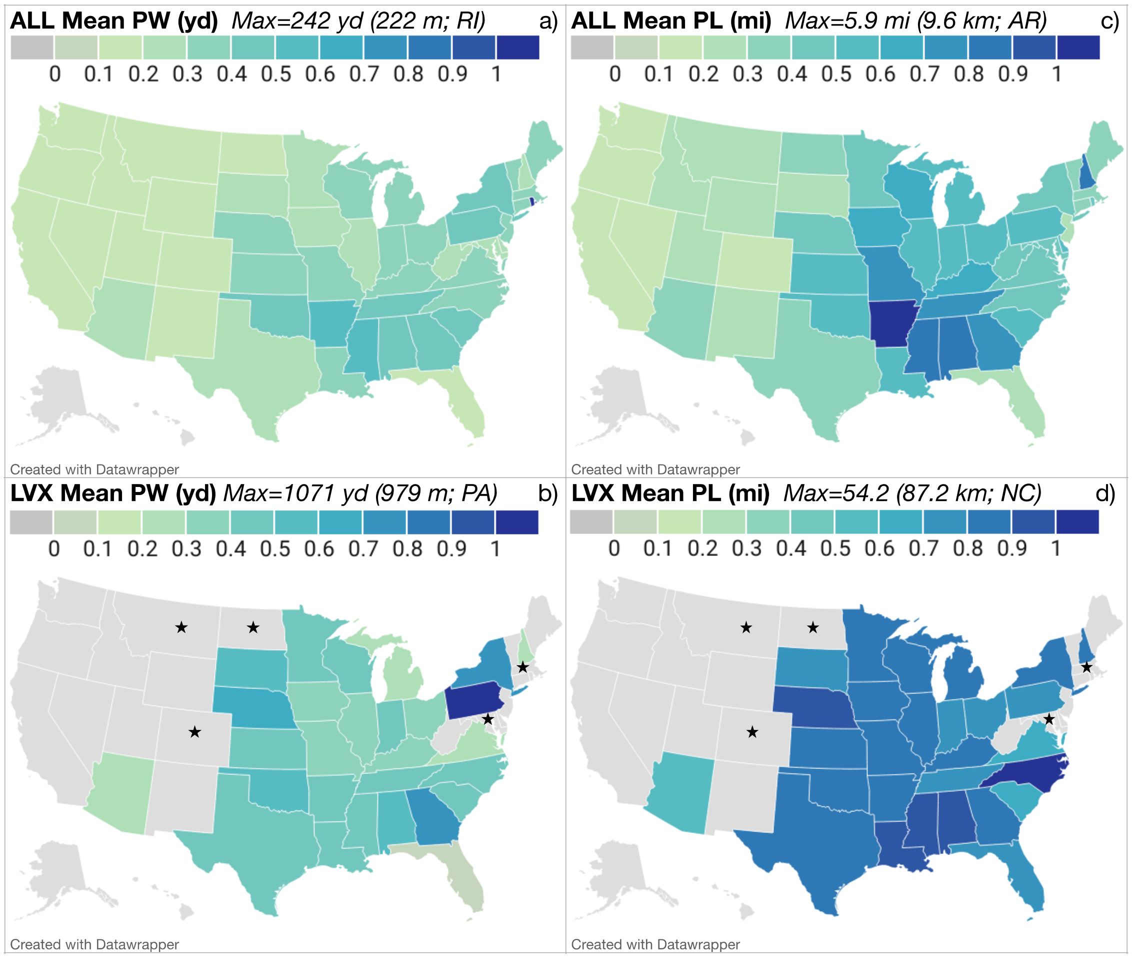

Figure 15: Maps of mean PW (yd) per state (left) and mean PL (mi) per state (right), made non-dimensional by dividing by the state value with the maximum mean value (maximum value displayed in top center of each panel along with the state having the classification's maximum), for ALL (top) and LVX (bottom) tornado PL categories. States with grey shading had either zero occurrences or had only one occurrence (annotated with a star; Colorado, Massachusetts, Maryland, Montana, and North Dakota) for the classification and thus, are not displayed. Hawaii, Alaska and the District of Columbia were excluded.

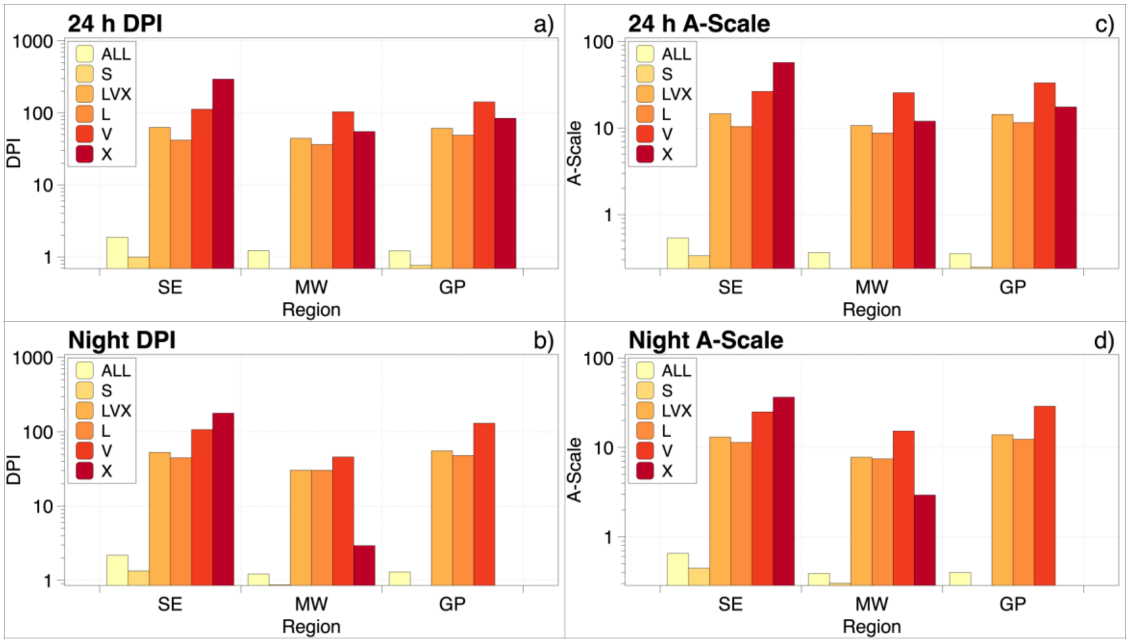

Figure 16: Log-linear bar charts of mean Destruction Potential Index (DPI; left) and mean area scale (A-scale; right) versus geographic region, Southeast (SE), Midwest (MW) and Great Plains (GP) for the ALL, S, LVX, L, V, and X tornado PL categories for 24 h (top) and night (bottom). Note the different scales on the vertical axes.

e. Month

May was the peak month for 24-h and night ALL and S tornadoes, with the bulk of these occurring from March through July, while the minimum for these tornadoes was in December (Fig. 17a, b). In comparison, the peak month for 24-h LVX, L, and X tornadoes was April, while April and May tied for V tornadoes (Fig. 17a). November had a secondary local peak for 24-h LVX, L, V, and X tornadoes and nighttime tornadoes of all PL categories. In contrast to other PLs, very few or no V and X tornadoes occurred from July to October and January to February (especially at night.) At night, April had the most LVX and L tornadoes (Fig. 17b), while the most night V and X tornadoes occurred in March and April, as well as in November and December. Though S and LVX tornadoes occurred in all months, longer-track nighttime tornadoes had increasingly sporadic monthly distributions with increasing PL, which was related to their smaller numbers.

April was the most prominent month for 24-h and ALL tornado-related deaths and injuries (Fig. 18a), while May had the maximum number of deaths and injuries associated with S tornadoes (Fig. 18b). Most of the 24-h deaths

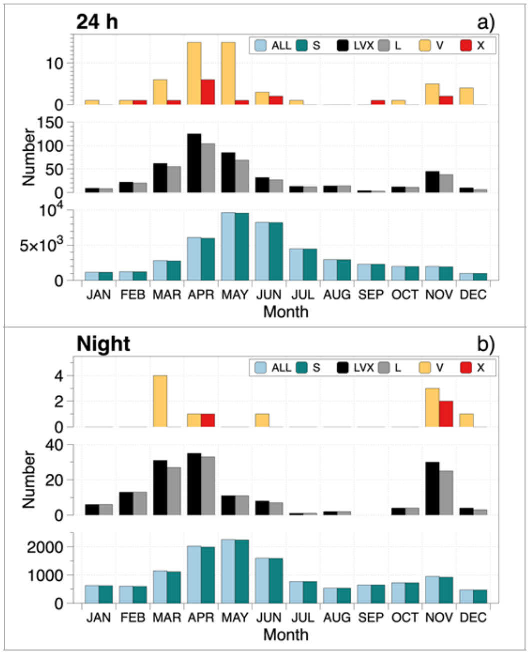

Figure 17: Linear-linear bar charts of number of tornadoes versus month for the ALL, S, LVX, L, V, and X tornado PL categories for a) 24 h and b) night. Note the different scales on the vertical axes. *Click image to enlarge*.

and injuries by LVX tornadoes (Fig. 18c) also occurred in April, consistent with the maximum frequency of 24-h LVX tornadoes. Even with two orders of magnitude more S than LVX tornadoes, the large number of deaths and injuries associated with April LVX (Fig. 18c) weighted the maximum for ALL toward April. Secondary maxima occurred in November for the 24-h deaths and injuries in all PLs categories. May had the second largest numbers of 24-h deaths and injuries for most long-track tornadoes (except X). At night, November was the maximum month for LVX, V, and X deaths and injuries (Fig. 18c, e and f), while March was the maximum month for L. In comparison, April was the maximum month for nighttime ALL and S tornado-related deaths and injuries.

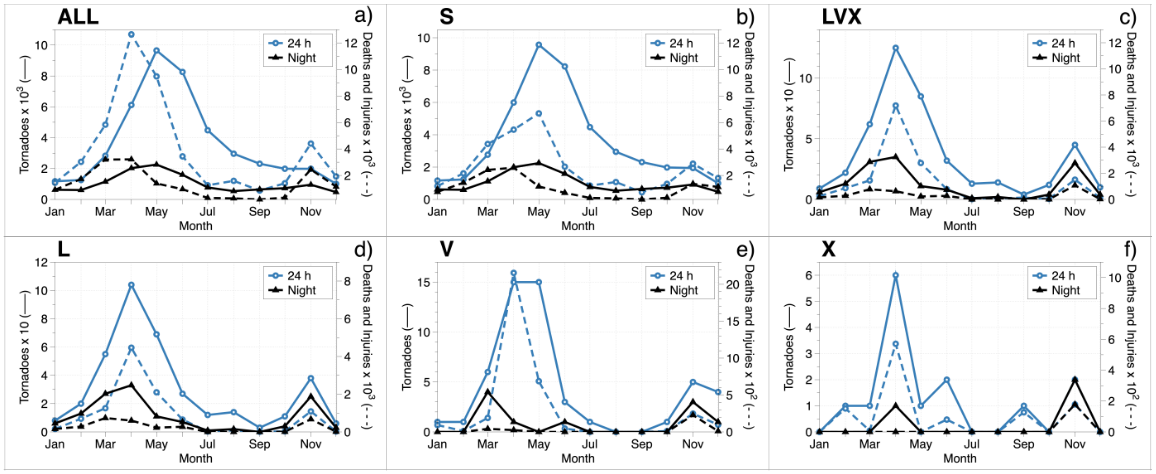

Figure 18: Line graphs of number of tornadoes (solid; left axis) and deaths and injuries (dashed; right axis) versus month for the a) ALL, b) S, c) LVX, d) L, e) V, and f) X tornado PL categories for 24 h (blue circles) and night (black triangles). Note the different scales on the vertical axes. *Click image to enlarge*.

To explore the interannual variability on the most prominent month for tornadoes, the extraordinary year of 2011, which had a record number of April tornadoes, was removed from the dataset (not shown). This did not change the finding that April had the most LVX tornadoes, and deaths and injuries from LVX tornadoes, but the April signal was not as prominent. The removal of 2011 tornadoes resulted in a shift in the maximum month for V tornadoes from an April-May tie to just May. Likewise, the maximum month of the number of deaths and injuries associated with V tornadoes, shifted from April to May with 2011 removed. The 2011 effect made a 13% difference for the number of May V tornadoes, and 25%, 21% and 67% difference for April LVX, L, and X, respectively. Overall, 2011 ranked a close second (after 2004) for the most 24-h ALL tornadoes, third for 24-h S, but clearly first for 24-h LVX, L, V, and X (Fig. 3).

The maximum Great Plains month of 24-h ALL and S annual tornadoes per 10 000 mi^2 (25 900 km^2; Fig. 19a) is May; however, the maximum month for the Southeast is April, and for the Midwest is June. The 24-h LVX maximum in April (see Fig. 18c) owes primarily to tornadoes in the Southeast (Fig. 19a). At night, the ALL and S maxima in April and May, and secondary maxima in November, were influenced strongly by the numbers of Southeast tornadoes (Fig. 19b). Likewise, for nighttime LVX, V, and X, the November maxima owed mostly to nocturnal long-track tornadoes in the Southeast, while the nighttime V maximum in March was due mostly to Great Plains tornadoes. Garner et al. (2021) showed nocturnal longer-track tornadoes were more likely in the Southeast than in the Great Plains, in part because of stronger nocturnal boundary-layer stabilization in the Great Plains.

Maps with a number on each state corresponding to the month with the maximum occurrence of ALL (Fig. 20a) and LVX tornadoes (Fig. 20b), as well as the month that starts the 2-mo period of maximum ALL (Fig. 20c) and LVX (Fig. 20d) tornado occurrences, support the results shown in Figs. 18–19. The LVX maxima occurred a month earlier than the ALL maxima in several of the

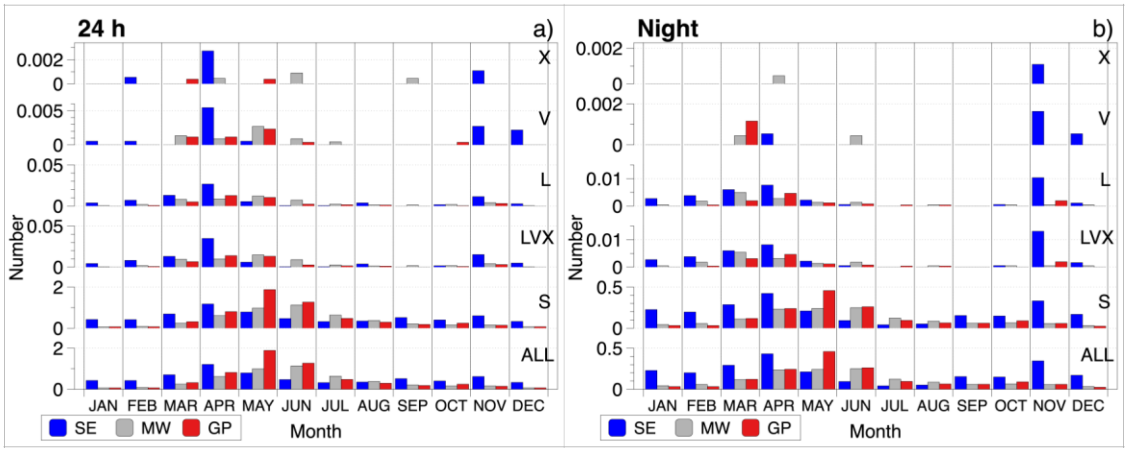

Figure 19: Linear-linear bar charts of annual number of tornadoes per 10 000 mi² (25 900 km²) versus month for the ALL, S, LVX, L, V, and X tornado PL categories for each geographic region, Southeast, (SE; blue), Midwest (MW; grey), and Great Plains (GP; red). a) 24 h and b) night. Note the different scales on the vertical axes. *Click image to enlarge*.

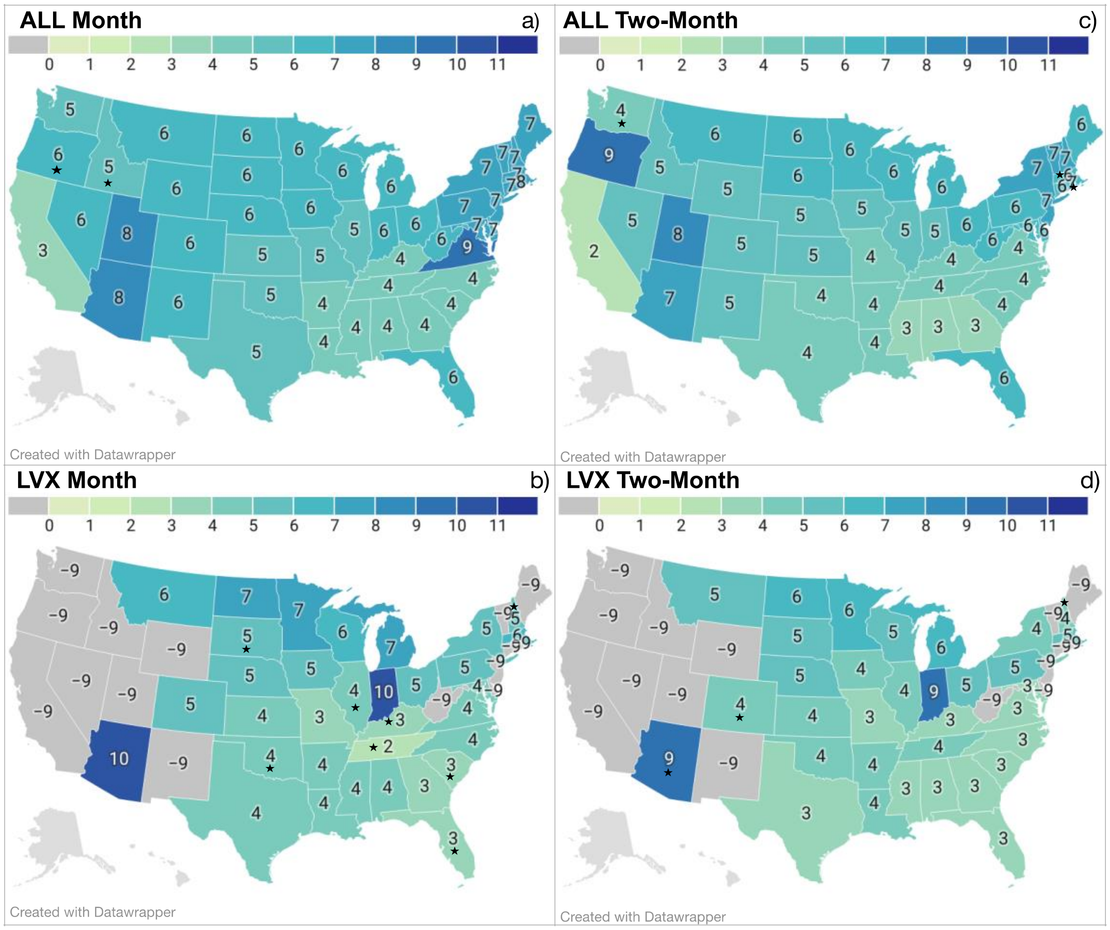

Figure 20: Maps of the 1-mo (left) and 2-mo (right) maxima of ALL (top) and LVX (bottom) occurrences by state in which paths began, for 24 h. States labeled with "–9" have no occurrences for the classification. Hawaii, Alaska and the District of Columbia were excluded. For a tie (asterisk), the earlier month was chosen. Appendix B lists tied-month states.

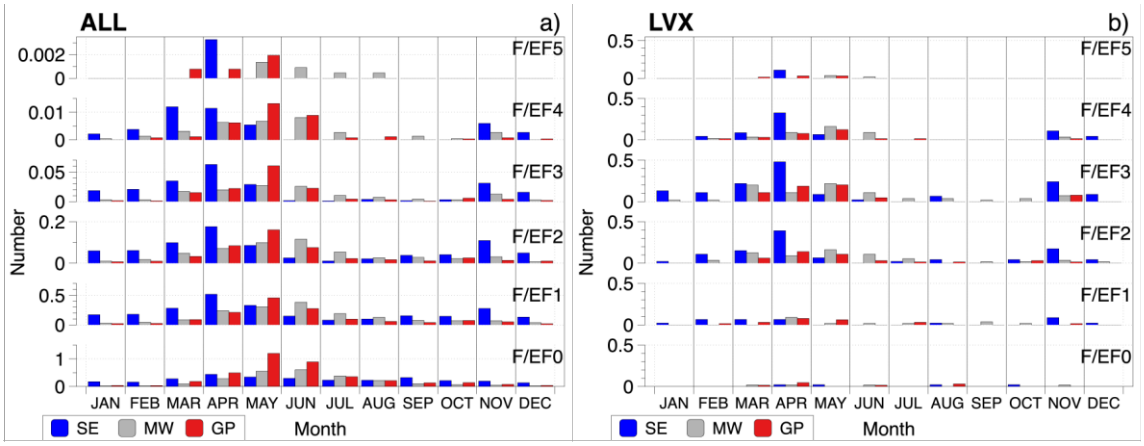

Figure 21: Linear-linear bar charts of annual number of tornadoes per 10 000 mi^2 (25 900 km^2) versus month for the ALL, S, LVX, L, V, and X tornado PL categories for each geographic region, Southeast (SE; blue), Midwest (MW; grey), and Great Plains (GP; red); and F/EF0–5 tornadoes. a) ALL and b) LVX tornado PL categories. Note the different scales on the vertical axes. *Click image to enlarge.*

Midwest states and most of the Great Plains states. In contrast, the LVX maximum was not a month earlier than for ALL, for some of the Southeast states where many of the LVX tornadoes occurred. The month of maximum occurrence for any PL tornado was generally later with increasing latitude in the springtime. The monthly patterns for ALL tornadoes approximately agree with B03 (their Fig. 9).

The largest annual numbers of tornadoes per 10 000 mi^2 (25 900 km^2), for the highest F/EF-scale ratings for ALL (Fig. 21a) and LVX (Fig. 21b), largely occurred in April for the Southeast, and one month and two months later in the Great Plains and Midwest, respectively. F/EF2–4 LVX tornadoes were common in late fall through early winter in the Southeast. The maximum number of deaths and injuries in April (Fig. 18c) is consistent with the most F/EF2–5 LVX tornadoes, particularly in the Southeast. Interestingly, more June LVX tornadoes occurred in the Midwest than other regions. In general, LVX tornadoes were more likely to have larger F/EF-scale ratings than shorter-track tornadoes, regardless of region or month, consistent with, for example, K78.

f. Local solar hour

The time of day for the formation of the largest number of ALL, S, LVX, and L tornadoes was in the afternoon, from about 1400–1900, while the peak hour for ALL, S, LVX, V, and X was 1600 [similar to, e.g., K78 and Krocak and Brooks (2018)]. LVX (L) tornadoes had bimodal peak hours at 1600 and 1800 (1800 and 1500). Most V tornadoes occurred over a narrower interval, 1500–1800, while X tornadoes were more sporadic. Only a small number of longer-track tornadoes occurred after 2000 local time, especially among the longest-track tornadoes from 0400–0900. This latter range of hours usually has the weakest solar heating and minima in the diurnal buoyancy fluctuations (e.g., Stull 1988).

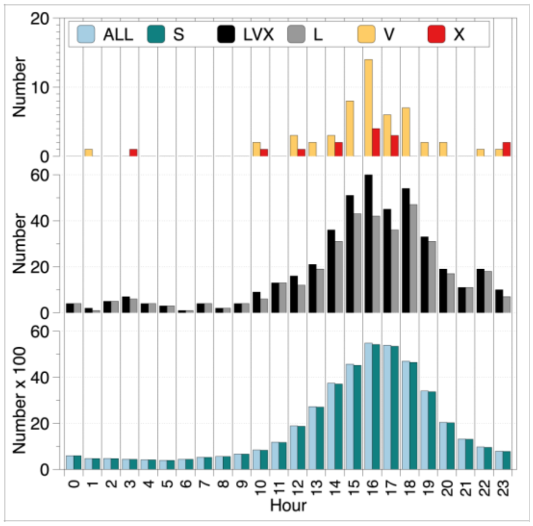

Figure 22: Linear-linear bar charts of number of tornadoes versus local solar hour for the ALL, S, LVX, L, V, and X tornado PL categories. Note the different scales on the vertical axes. *Click image to enlarge.*

The largest numbers of deaths and injuries associated with ALL and S tornadoes were in the 1600 hour, as were the largest tornado frequencies (Fig. 23a, b). Note that the bimodal peaks at 1500 and 1700 in the number of LVX deaths and injuries is offset an hour earlier than the bimodal peak in the LVX tornadoes (Fig. 23c). Similarly, deaths and injuries with L tornadoes (Fig. 23d) were most at 1700 with a single peak, despite the bimodal peak hours for L tornadoes (1800 and 1500). Deaths and injuries from V and X tornadoes (Fig. 23e, f) were about 1 and 2 h earlier, respectively, than the peak tornado frequencies, though X tornadoes had a secondary peak at 1700. However, there were only two X tornadoes at 1400, and seven total X tornadoes for the hourly bins 1600 and 1700.

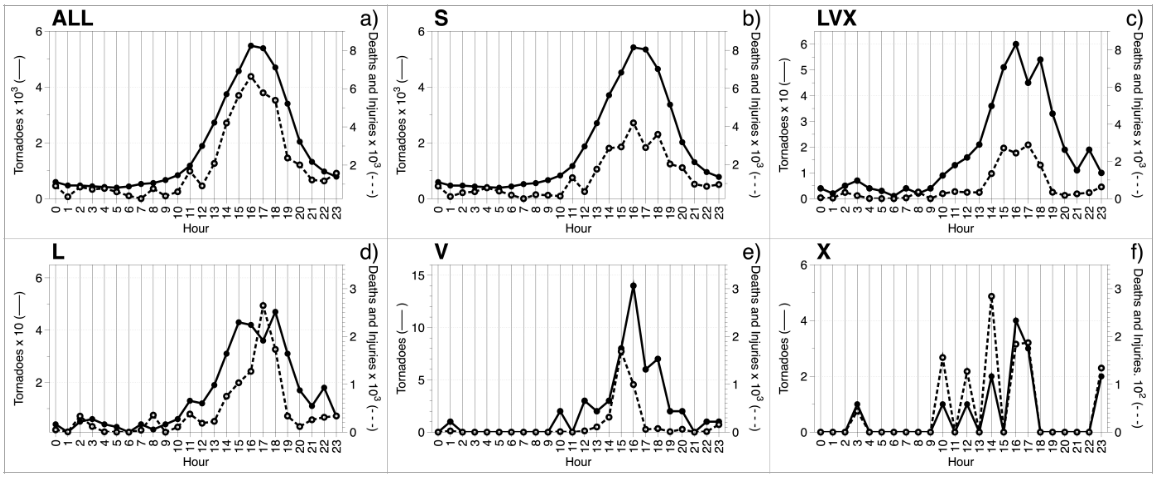

Figure 23: Line graphs of number of tornadoes (solid; left axis) and deaths and injuries (dashed; right axis) versus local solar hour for the a) ALL, b) S, c) LVX, d) L, e) V, and f) X tornado PL categories. Note the different scales on the vertical axes. *Click image to enlarge*.

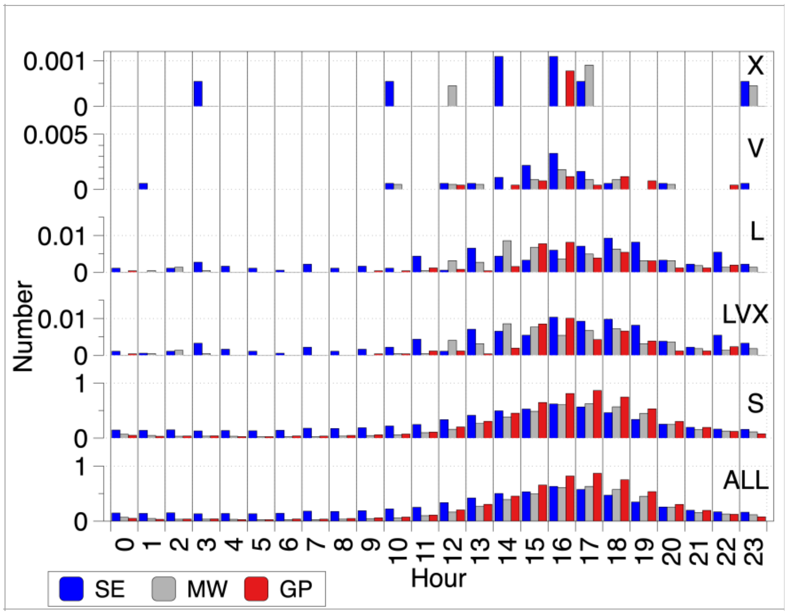

Figure 24: Linear-linear bar charts of annual number of tornadoes per 10 000 mi^2 (25 900 km^2) versus local solar hour for the ALL, S, LVX, L, V, and X tornado PL categories for each geographic region, Southeast (SE; blue), Midwest (MW; grey) and Great Plains (GP; red). Note the different scales on the vertical axes.

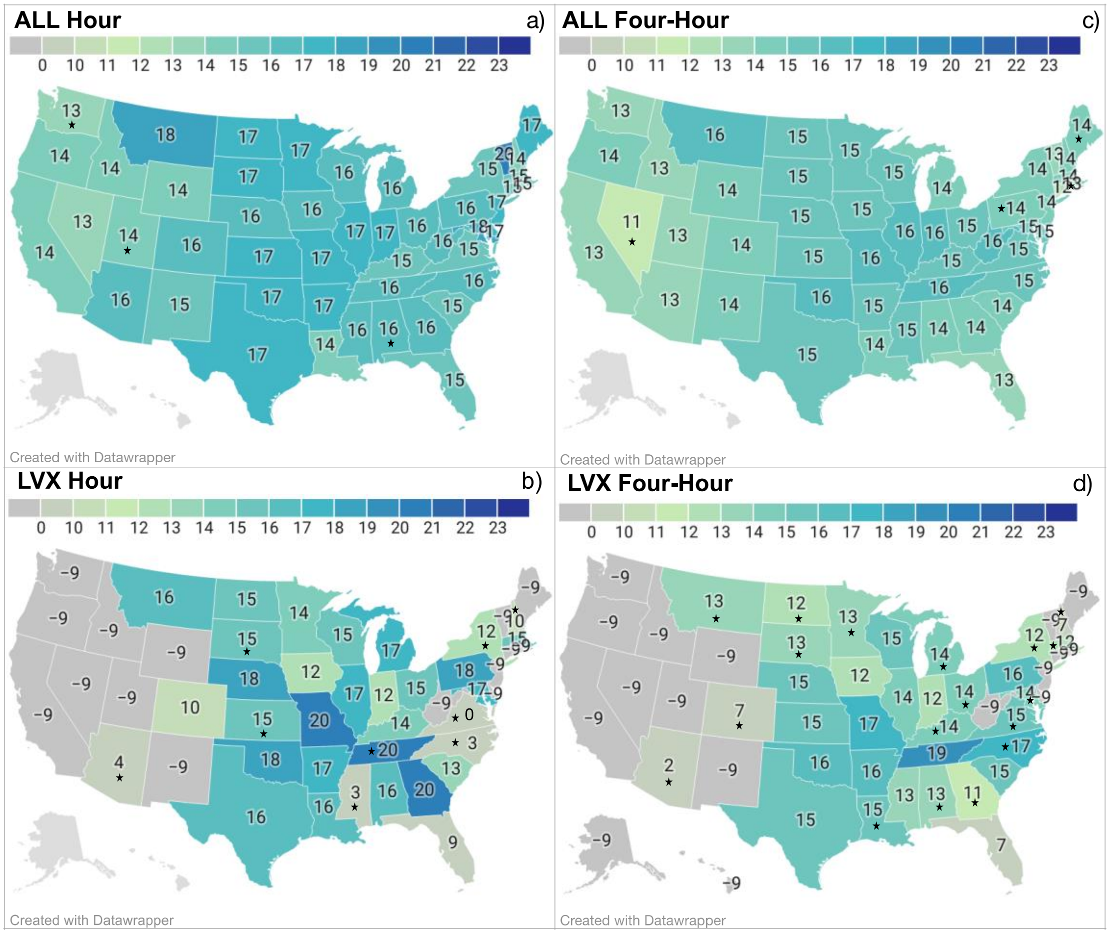

Figure 25: Maps of the 1-hr of maximum (left) and the 4-h maximum (right) of ALL (top) and LVX (bottom) occurrences by state in which they began for 24 h. States labeled with "–9" have no occurrences for the classification. Hawaii, Alaska, and District of Columbia data were excluded. If there was a tie, the earlier hour was chosen and the state was marked with an asterisk. Appendix C lists tied-hour states.

The largest annual numbers per 10 000 mi^2 (25 900 km^2) of ALL and S tornadoes occurred slightly earlier in the Southeast than in the Midwest and Great Plains (Fig. 24). In comparison, the peak LVX hour was about the same as ALL for the Southeast, but was earlier for the Midwest and Great Plains. For LVX and L tornadoes, the peak hour generally was earliest in the Midwest and latest in the Southeast. Southeast LVX and L tornadoes formed over a much broader number of hours than in the Midwest and Great Plains, where narrower portions of the afternoon were favored. For unknown reasons, a minor, early morning local maximum (~1100–1300) for LVX tornadoes appeared in all regions. More tornadoes occurred during the overnight hours in the Southeast for all PL categories than in either the Midwest or the Great Plains, in agreement with K78. No V and X tornadoes occurred in any of the regions from 0400–0900. Though Figs. 22–23 do not show earlier formation hours for most longer-track tornadoes than for ALL and S, earlier formation times are indicated for some of the classifications, when considering geographic region and state subsets (Figs. 24–26).

The hour and starting-time hour of the 4-h interval (following Krocak and Brooks 2018; note they used UTC time), for the maximum number of ALL tornadoes by state (Fig. 25a, c; states with tied hours are denoted with an asterisk; the earlier hour is shown) show both of these were typically between 1600–1700 for the Great Plains and 1400–1600 for the Midwest. For the Southeast states, the hour of the maximum number of tornadoes was typically slightly earlier from 1500–1700, while the 4-h interval maximum was from 1300–1600 (Fig. 25c).

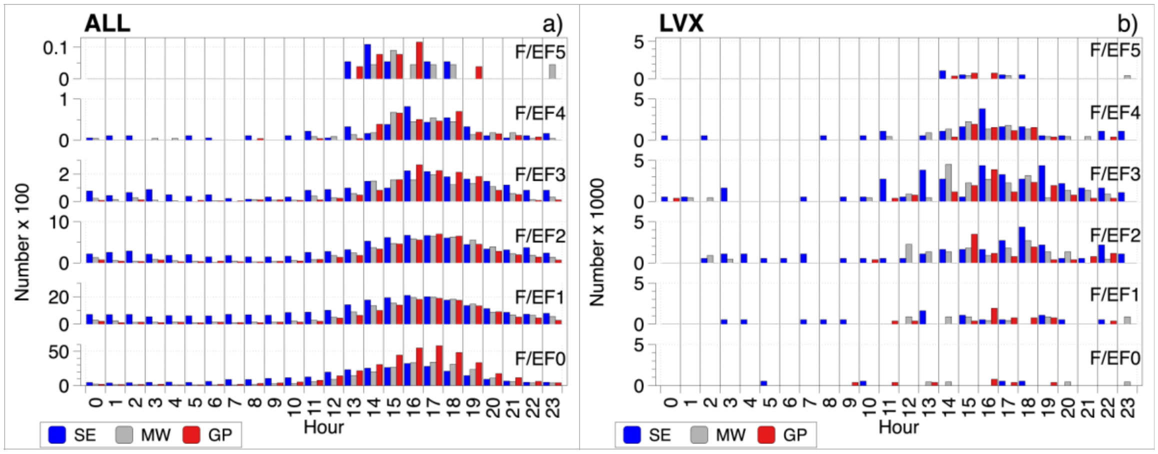

Figure 26: Linear-linear bar charts of annual number of tornadoes per 10 000 mi^2 (25 900 km^2) versus local solar hour for the ALL, S, LVX, L, V, and X tornado PL categories for each geographic region, Southeast (SE; blue), Midwest (MW; grey) and Great Plains (GP; red), and F/EF0–5 tornadoes. a) ALL and b) LVX tornado PL categories. Note the different scales on the vertical axes. *Click image to enlarge.*

There were many states with ties (equal maximum numbers) for the peak formation hour of LVX tornadoes (Fig. 25b, d) and for many states the maximum hour for LVX tornadoes was earlier than that for ALL tornadoes. The 4-h interval might be more useful (Fig. 25d) for LVX tornadoes; the starting hour is definitely earlier for most states in the Midwest and Southeast than for ALL tornadoes, but is more similar to that of ALL tornadoes for the central Great Plains states.

As F/EF rating increased from F/EF3–F/EF5 in all geographic regions, the largest annual area-weighted number of ALL tornadoes mostly occurred at progressively earlier hours (Fig. 26a), as well as at earlier hours in the Southeast than in the Great Plains and Midwest. For F/EF0–2 events, the hourly distribution for the Southeast was skewed earlier and more broadly than in the other two regions, with the Midwest and Great Plains having more similar distributions to each other. Numbers for F/EF3–5 show more focused maxima for all regions in the late afternoon hours, while prominent numbers still occurred overnight in the Southeast for EF/F3–4. In contrast to ALL, higher damage-rated LVX tornadoes mostly occurred at slightly earlier and more focused ranges of hours (Fig. 26b) in the mid- to late afternoon, especially in the Great Plains. The largest normalized numbers of LVX had F/EF2–4 ratings for all regions.

5. Summary and conclusions

The findings from this climatology of tornadoes in the United States from 1979–2018, using tornado-track PL stratification categories (Table 3) of all (ALL), PL >0 mi or 0 km; short (S), PL <30 mi or 48.3 km; long-track sum (LVX), PL ≥30 mi or 48.3 km; long (L), [30–60) mi or [48.3, 96.6) km; very long (V), [60, 90) mi or [96.6, 144.8) km; and extremely long (X), PL ≥90 mi or 144.8 km, include that LVX tornadoes:

- Made up <1% of all tornadoes;
- Occurred mainly in states east of the Rocky Mountains;
- Were generally wider than S tornadoes;
- Caused over 32% of deaths and injuries, despite constituting <1% of tornado occurrences;
- Typically had damage ratings ≥F/EF2 (peak F/EF3) and typically had higher damage ratings than S tornadoes;
- Occurred more often and with more deaths and injuries in the Southeast than either the Midwest or Great Plains;
- Had larger average A-scale and DPI values than S tornadoes;
- Occurred mostly in April and May, with those in the Southeast often occurring in earlier months;
- Occurred mostly between midafternoon to early evening (1400–1900), and much less frequently after early evening through midmorning;

- Had a peak formation hour at 1600 local solar time (also true for ALL, S, V and X), though L tornadoes had a peak formation and secondary peak at 1800 and 1500 local solar time, respectively;
- Were much less likely during the nighttime than S tornadoes;
- Were more frequent during nighttime in the Southeast than nighttime in the Midwest or Great Plains; and
- Often occurred during outbreak days of >5 (10) tornadoes 85% (74%) of the time.

The accuracy of climatology studies is dependent on the accuracy of the datasets and the rigor of the methodology. Besides data issues and other limitations described in section 2, an important limitation of this study is LVX and L tornadoes made up <1% of all tornadoes in the dataset, with V and X tornadoes even more rare. *The results are limited by the small sample sizes of the V and X categories and to some extent the L and LVX categories. Small sample sizes, combined with interannual variability, also preclude the possibility of discerning meaningful long-track tornado temporal trends from the data. Finally, the results could be affected by reporting and recording errors. Thus, care should be taken when making generalizations.*

Another limitation was that only a single threshold value (30 mi or 48.3 km) was examined as a lower bound for long-track tornadoes. This threshold was based on supercell characteristics and evolution, which are not necessarily similar to those associated with of other storm types, such as QLCS storms or mesoscale convective vortices (both of which are unlikely to be associated with long-track tornadoes). Other PL stratification thresholds that are dynamically consistent or statistically determined (e.g., G21) should be examined more thoroughly.

Since 2018, there have been eight V tornadoes: three in 2019, three in 2020, and two in 2021. There also have been two X tornadoes, both on 10 December 2021. All of these 2019–2021 tornadoes had PLs supported by extensive NWS damage surveys and are in Storm Data. With 52 total V tornadoes and 14 X tornadoes for the entirety of 1979–2018, the occurrence of eight V and two X in the period, 2019–2021, is quite remarkable. Nevertheless, 2011 had eight V and four X tornadoes, which further highlights the extraordinary nature of that year.

Forecasters and emergency-management personnel can use the results herein to plan for and respond to potential long-track tornadoes, including consideration of geographically susceptible states and regions, or critical times of the day and night. Also, a better understanding of predictive sounding parameters and the radar evolution of storms that produce long-track tornadoes could improve forecasts for these extreme events. Based on the success of the significant tornado parameter (STP; Thompson et al. 2003; Thompson et al. 2004) and the development of a violent tornado parameter (VTP; Hampshire et al. 2018) to diagnose environments favorable for "significant (EF2/EF3)" and "violent (EF4/EF5)" tornadoes, severe-storm forecasters might benefit from a long-track tornado parameter (LTTP) that is currently being developed by the authors. Finally, a climatology for long-track tornadoes for 10, 20, 30, and 40+ y periods is also underway to examine, for example, regional changes with time, while trying to account for natural variability.

ACKNOWLEDGMENTS

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APPENDIX A: Glossary of acronyms

ALL	*Path length category for tornadoes of any path length*
S	*Path length category for tornadoes with path length <30 mi or 48.3 km*
LVX	*Path length category for tornadoes with path length ≥30 mi or 48.3 km*
L	*Path length category for tornadoes with path length [30–60) mi or [48.3–96.6) km*
V	*Path length category for tornadoes with path length [60–90) mi or [96.6–144.8) km*
X	*Path length category for tornadoes with path length ≥90 mi or 144.8 km*
PD	*Path duration in minutes or hours*
PL	*Path length in mi (km)*
PW	*Path width in yd (m)*
F/EF scale	*Fujita/Enhanced Fujita damage-rating scale*
A-scale	*Area scale*
DPI	*Destruction Potential Index*
SE	*Southeast*
MW	*Midwest*
GP	*Great Plains*

APPENDIX B: Tied-month states for tornado PL categories (Fig. 20)

Tied months for ALL included: Idaho, May and June (36 each); and Oregon, June, September and October (13 each). Tied months for LVX included: Florida, March and August (2 each); Illinois, April and May (5 each); Kentucky, March and November (3 each); New Hampshire, May and July (1 each); Oklahoma, April and May (12 each); South Carolina, March and April (3 each); South Dakota, May and June (1 each); and Tennessee, February and April (4 each). Tied 2-mo intervals for ALL included: Massachusetts, June and July (37 each); Rhode Island, July and August (7 each); and Washington, April and May (35 each). Tied 2-mo intervals for LVX included: Arizona, September and October (3 each); Colorado, April and May (1 each); and New Hampshire, April, May, June and July (1 each).

APPENDIX C: Tied-hour states for tornado PL categories (Fig. 25)

Tied hours for ALL included: Alabama, 16 and 17 (133 each); Utah, 14 and 16 (14 each); and Washington, 13 and 15 (14 each). Tied hours for LVX included: Arizona, 4, 5 and 11 (1 each); Kansas, 15 and 16 (8 each); Mississippi, 3 and 13 (4 each); New Hampshire, 10 and 20 (1 each); New York, 12, 15 and 16 (1 each); North Carolina, 3 and 18 (2 each); South Dakota, 15 and 16 (1 each); Tennessee, 20 and 22 (3 each); and Virginia, 0, 10, 17, and 18 (1 each). Tied 4-h intervals for ALL included: Maine, 14 and 15 (36 each); Nevada, 11, 12, and 13 (40 each); Pennsylvania, 14 and 15 (307 each); and Rhode Island, 13 and 14 (8 each). Tied 4-h intervals for LVX included: Alabama, 13 and 14 (15 each); Arizona, 2, 3, and 4 (2 each); Colorado, 7, 8, 9, and 10 (1 each); Georgia, 11, 12, 13, 14, 15, 17, and 20 (4 each); Kentucky, 14 and 16 (6 each); Louisiana, 15 and 16 (4 each); Maryland 14, 15, 16, and 17 (1 each); Massachusetts, 12, 13, 14, and 15 (1 each); Michigan, 14, 15, 16, and 17 (3 each); Minnesota, 13 and 14 (6 each); Montana, 13, 14, 15, and 16 (1 each); New Hampshire, 7, 8, 9, 10, 17, 18, 19, and 20 (1 each); New York, 12, 13, 14, and 15 (2 each); North Carolina, 17 and 18 (4 each); North Dakota, 12, 13, 14, and 15 (1 each); Ohio, 14 and 15 (5 each); South Dakota, 13, 14, and 15 (2 each); and Virginia, 15, 16, and 17 (2 each).

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REVIEWER COMMENTS

[Authors' responses in *blue italics.*]

REVIEWER A (Makenzie J. Krocak):

Initial Review:

Recommendation: Accept with minor revisions.

Overview: This paper adds to the tornado climatology literature by presenting updated data and new stratifications to the analysis. I believe there are a few changes that could be made to improve the readability, but overall, it is well-written.

Thank you for your helpful and insightful review, which we think has led to improvement in our manuscript. Major changes that address all three reviewers are stated first. Specific responses to each of your comments are included afterward.

[Editor's note: The following general response was made to each reviewer, and only will be reproduced here with the reply to Reviewer A, for brevity. Individual replies essentially duplicating or reiterating parts of this general reply also will not be reproduced, also to save space.]

"Double-column" figure format may or may not extend completely to the side margins depending on the final layout of the paper.

Major changes to the paper include:

• The dataset has been filtered further (beyond removing segment =2 entries) to remove AK, HI, PR, and DC, as well as all cases where path length (PL)=0 and F/EF-scale was not defined, which resolves the issue of the ALL category including "extra" cases not included in the other classifications. This resulted in the removal of 279 cases (~1% of all tornadoes), which did not change the number of LVX, L, V, or X tornadoes in the dataset.

Text:

- *Total rewriting, reordering and reorganization of sections 1–3.*
- *The new sections 1–3 include:*
  1. *Introduction (includes motivation, context, purpose, and review of the relevant literature),*
  2. *Data and methods (includes limitations of the dataset and methodology), and*
  3. *Tornado path length stratification*
- *A new Table 1 was added that lists prior studies that considered tornado PL and their thresholds for long-track and very long-track tornadoes.*
- *All figures are presented and discussed in section 4 Results now (and not earlier).*
- *A new subsection, 4c, was added on mean path width (PW; to accommodate Reviewer A's comments regarding PW) and DPI and A-scale were given their own subsection, 4d.*
- *Rather than listing specific numerical values and relationships, where possible, more general*
- *interpretations are offered (as specifically suggested by Reviewer C and an informal reviewer prior to the original submission).*
- *The submitted Table 2 of notable long-track or long-duration tornadoes was removed and any specific cases are stated in the text.*
- *Essentially all acronyms have been removed except: ALL, S, LVX, L, V, X, PD, PL, PW, DPI, (NCEI, SPC, QLCS [retained as suggested by Reviewer A]), NCDC (which is acceptable via EJSSM References Guide), and F/EF-scale. We have included a Glossary at the end of the paper for the acronyms which were retained.*

***Figures**:*

- *All fonts were increased to 28 pt for axis labels and axis numbers (except for the x-axes in Figs. 1, 17, 19, 21, which were slightly smaller 17% than 28 pt). Title labels were made 30% greater than 28-pt font. However, some of these will appear somewhat bigger or smaller depending on the final format size of the figure (single-column width, two-column width or in between).*
- *White space was cropped out of all figures wherever possible to increase the content to white-space ratio.*
- *Titles for each sub-panel figure were removed and replaced with simpler, much larger labels.*
- *Figs. 3, 17 and 22 were made taller and changed from six axes to three axes, with coupled color schemes to aid visibility. Figure 3 was also made double-column width, since the x-axis had 40 (year) categories. This represents a sort of compromise explained in detail in responses to Reviewer B.*
- *Figs. 12, 19, 21, 24, 26 (which are still six-axis figures and include data for the three geographic regions) were made taller and all but Fig. 12 were made two-column width for increased readability and to address the concerns of all three reviewers. In addition, the color scheme was changed to blue, grey and red for increased contrast. These color changes are also reflected in Fig. 7. Figure 12 was not made two-column width since there were fewer x-axis categories (F/EF-scale) and was therefore easier to read than most other six-axis figures.*
- *Figs. 6, 18, and 23 (line graphs) were transposed (from 3x2 to 2x3 panels), made taller, and formatted to double-column width.*
- *Figs. 9–11, and 15 (maps) now display map data that was normalized by the maximum state value (displayed in the titles) in each classification in order to facilitate intercomparisons. (Data range from 0–1 for each US state.)*
- *Figs. 9–11 (maps): Numeric labels on each state were removed since using the Datawrapper software, there was no way to prevent them from overlapping without making them so small that they would become unreadable. (Perhaps for future studies a different mapping software program will be explored.)*
- *Figs. 9–11,15, 20, and 25 (maps) were edited so that as much white space as possible was removed from each panel and legend titles were made larger where possible.*
- *Figs. 3 and 4 were switched in order of presentation and numbering*
- *A panel d was added to Fig. 5 to compare the current results to those of Kelly et al. (1978) to address a query raised by Reviewer A.*
- *All figures that display data for geographic regions (8, 12, 19, 21, 24, and 26) have been adjusted to show the area-normalized numbers (per 10,000 mi2 or 25,900 km2) except for Fig 16 which depicts mean A-Scale and mean DPI.*
- *Three new figures were added in the new subsection 4c (Figs. 13, 14, and 15 to accommodate concerns raised by Reviewer A), that include PW.*
- *The original Fig. 22 was removed completely.*

Substantive Comments:

The thought process in the paragraph (starting with "Next, it is assumed...) is interesting but also speculative. Given the spread of mesocyclone life cycle times identified by Adlerman et al. (1999) and others (could you provide citations for the others?), is it useful to use the mean value of 40 min? The assumption that is most concerning to me is the fact that the time between low-level mesocyclone formation and tornado formation is 30 min. If this were true, the operational benefit would be significant. It comes across as too speculative as it is written currently, but perhaps would be suitable to keep if the authors commented again on the uncertainty associated with these estimates.

Thank you for your concern on this issue, which was also raised by Reviewer B. This discussion has been expanded to include simulation and observational support for the values. Additionally, more comments about the uncertainties have been added. However, it remains a difficult problem to tie tornado PL stratification to storm characteristics and evolution. We have reinforced that this method is not exact and is used only for guidance in developing thresholds/stratification for supercell associated short- and long-track tornadoes. Our intent was not to provide forecast guidance, which we believe is not possible from this discussion.

Data and methods: What is the reason for including unknown PL for the ALL tornadoes category? It seems like that would make comparisons between S/L/V/X and ALL more difficult.

We agree completely. (This point was also raised by Reviewer B.) The dataset has been filtered further (beyond removing segment =2 entries) to remove AK, HI, PR, and DC, as well as all cases where path length (PL)=0 and F/EF-scale was not defined, which resolves the issue of the ALL category including "extra" cases not included in the other classifications. This resulted in the removal of 279 cases (~1% of all tornadoes), which did not change the number of LVX, L, V, or X tornadoes in the dataset. All figures and tables have been redone to reflect this change. There is no change in the interpretation of the results for ALL and S tornadoes.

Results and discussion: It's worth noting at least once that the sample sizes for the V and X categories are so small that there can't be any generalizations drawn. Saying that there were not any nocturnal DIs from X tornadoes in a specific region is not very useful when there were not many (any) X tornadoes in that specific region to begin with.

Thank you for drawing our attention to this. The reference to zero deaths and injuries for cases having no tornadoes has been removed. The statement regarding small sample sizes of V and X tornadoes is now located in the last paragraph of section 2.

[Minor comments omitted…]

Second Review:

Recommendation: Accept.

General Comment: After looking over the reviews and the revised manuscript, I think the authors have addressed my comments reasonably well and the paper is suitable for publication.

REVIEWER B (Roger Edwards):

Initial Review:

Recommendation: Accept with major revisions.

Overview: The manuscript describes characteristics and analyses of a lightly filtered subset of the U.S. tornado database, pertaining to a supercell-behavior-motivated set of thresholds for tornadic path length. The research concentrates on long-, very long- and extremely long-track tornadoes, with breakdowns by months, hour of day, geographic regions, DPI, and Area Scale.

My recommendation is "accept with major revision". The main value is in a novel assessment of climatology of impactful tornadoes in terms of path length, also implying longevity and relatively large affected area in most cases. Tornado climatology often has been examined in path terms, as cumulatively cited by the authors, those papers' citations, and this review's reference list. Nonetheless, path length is seldom evaluated on its own, in bulk, across decades of climatology, essentially independently from damage rating (which is subjective, as the authors rightly note), path width and other variables native to the data. As such, this effort provides a potentially useful and valuable angle on understanding tornado climatology, and conceptually meets formal scientific standards for publishability.

This is a large paper with a lot of figures, and will need a lot of work to get there, however—most of which is a "major" aggregation of "minor" fixes and improvements. I also have several substantive comments that can be interpreted as major or minor, but which should be straightforward to address, given the nature of the SPC whole-tornado data and the segmented Storm Data that feeds it. Many minor scientific comments (mainly involving clarification, reconsidering a statement, or citing unsupported statements) won't be included in the substantive review, but still will need to be addressed.

No show-stoppers or impossibilities appear that preclude proceeding, as long as the substantive scientific comments are addressed satisfactorily, and the very large number of minor/technical and verbosity issues are remedied. Please be assured, they're all suggestions for improvement, intended to help the authors to publish this work at utmost excellence. Cleaning up the many technical and wording problems now will help a lot with readability for Round-2 reviewers, then if accepted, will help a great deal in copy editing, technical editing and final-draft readership. Also, wording can be tightened up in several places and made more specific in others, with more active verbs. Acronyms are much too numerous, to the point of causing reader confusion. This is a straightforward fix too. I do wish to read the next draft and accompanying point-by-point responses.

Thank you for your helpful and insightful review, which we think has led to improvement in our manuscript.

Substantive scientific comments (in chronological order):

Throughout: Conflation of damage rating with tornado intensity: This is a borderline substantive comment, since it appears often in the paper, and is a common problem in several papers I've reviewed, but also, is easy to fix through simple rewording. F or EF rating is not rigidly synonymous with tornado intensity, because the true strength of most tornadoes is unknown (Doswell and Burgess 1988; Edwards et al. 2013, both already cited in paper) and probably underdone, given the small percentage of tornadoes for which mobile-radar data are available (Wurman et al. 2021, already cited in paper). Please clarify and reword every instance of "intensity" in this context by replacing with "rating", "damage rating" or "damage intensity".

Agreed. All occurrences have been changed to "damage rating" or similar wording, except in the Introduction, paragraph 2, where the wording is quoted from Kelly et al. (1978) and in section 5, paragraph 4 where Thompson et al. (2003), Thompson et al. (2004) and Hampshire et al. (2018) are quoted.

Section 1: Time-binning choices: The authors' selection of 2300–0700 local solar time as "nighttime" is simple and easy to do, and explicitly accounts for temporal oversmoothing and discontinuities inherent to time zones. However, it also seems arbitrary and sometimes unphysical, despite being stated as related to "little or no solar heating". The trouble with using that time bin instead of local sunrise and sunset times for year-round tornadoes is that the latter (and their influences on the diurnal heating and nocturnal cooling cycles of convective activity) vary by season and latitude–and by a few hours per full solar day at both sunrise and sunset at higher latitudes. That's just physical reality imparted by Earth's axial tilt through each orbit. If you were looking at tornadoes in a single season this way (say, tropical-cyclone tornadoes in late summer and early fall), it wouldn't be much of an issue. But you're examining year-round climatology inclusive. Options exist, among them:

- Just use local sunrise and sunset. This is my preference for work of this nature, claiming to represent diurnal heating/cooling cycles year-round. If not using local sunrise/sunset, why not? Do a clearer job of justifying that choice. However, if the objective here is to analyze and depict day and night relationships truest to the daily, year-round heating/cooling cycles, as is suggested, then local sunrise/sunset times should be used. Otherwise, restate the objective. Or…
- Status quo analytically, but: If the objective is to reflect such cycles at their (oversimplified) loosest, restate the time-binning choice explicitly as both arbitrary and season- and latitude-invariant, and as only a very coarse approximation of the daily diabatic surface thermal cycles. Then justify why using 2300, as opposed to an earlier hour when there's still no insolation (such as 2200, 2100, or even all the way back to 1900 local in wintertime at most latitudes). Or…
- Alternatively, a compromise could be still-arbitrary (but somewhat more physically meaningful) season-dependent day/night bins of local solar time—say, one for the solar summer period, one for the winter period, and one for spring/fall.

We agree with all of your comments regarding delineation of nighttime and believe each of the suggestions you provide are reasonable, with each having its own set of pros and cons. We chose 2300–0700 local time *in our paper for a couple reasons and have chosen to retain this designation. We review the various nighttime designations of prior studies in section 2. Also, we have included justifications for our choice in that it preserves the uniformity of the hours considered and assures that the majority of all nighttime cases occur at least 2 h after local sunset. Our methodology is probably most similar to Kis and Straka (2010) or perhaps Ashley et al. (2008).*

Section 1: Reasons for short-track (weak?) tornado proliferation since 1950s: Re: "There have been more, shorter-track tornadoes…": Why? The likely related growth in number of weak (F/EF0 and F/EF1) tornadoes has been well-documented (e.g., Verbout et al. 2006), with reasons stated in the literature. This includes the strong association with WSR-88D deployment shown in Fig. 2 of Agee and Childs (2014). Other reasons offered have included increases in spotters and chasers, population, media attention, cell phones, etc. (e.g., Edwards et al. 2013 and some references therein; Weiss et al. 2002). A decades-old (K78) association between path length and tornado rating is cited. How quantitatively valid is the connection in the >40 y since, and is it strong enough—including data from all the time since their work—that the same reasoning for F/EF0 increases applies to S tornadoes as well?

You mentioned the DPI A-scale work of Thompson and Vescio, as well as the B04 findings describing data spread, but over a decade has elapsed since their work too. You already have the data at hand to test the PL vs. rating relationship independently over your much-longer dataset. Given how much attention it gets (at least a couple paragraphs), and the fact you've got the data at hand to test it, the bulk quantitative relationship of length to rating in your dataset is worth briefly analyzing and stating in section 1.

Thank you. These are excellent points. We have broken down our response into parts A and B below to address your question(s).

A. *We believe you are asking whether the reasons for the increase of F/EF0 tornadoes might also explain the increase in S tornadoes. Comparison of the figure below with Fig. 2 of Agee and Childs (2014) shows the same increase ~1991 (or just before) that they show. However, we actually see somewhat of a decrease in the mean annual numbers for both F0 and S tornadoes over the most recent decade, conceding significant interannual variability.*

   The figure below (provided for this review response, but not included in the manuscript) also shows the same general pattern for the annual numbers for each of F/EF0 and S tornadoes. Thus, without definitive proof, we can only speculate that the reasons for the increase in F/EF0 tornadoes might also be related to the increase in the number of S tornadoes, especially since K78, Brooks (2004), Garner (2007) and Elsner et al. (2014) and our Fig. 5 document an association between lower F/EF-scale ratings and smaller PLs. From 1979-2018, (E)F0 tornadoes constituted 55% of all the S tornadoes, while F1 made up 32% of all S tornadoes, so that the combination of F/EF0–1 made up 87% of all S tornadoes. In comparison, K78 showed "weak" tornadoes made up 72% of PL0–1 (short-track PL0–1<32 mi or 51.5 km) tornadoes for their years, 1950–1976 (their Table 5). We do not know how much the filtering of the dataset by K78 affected their percentages.

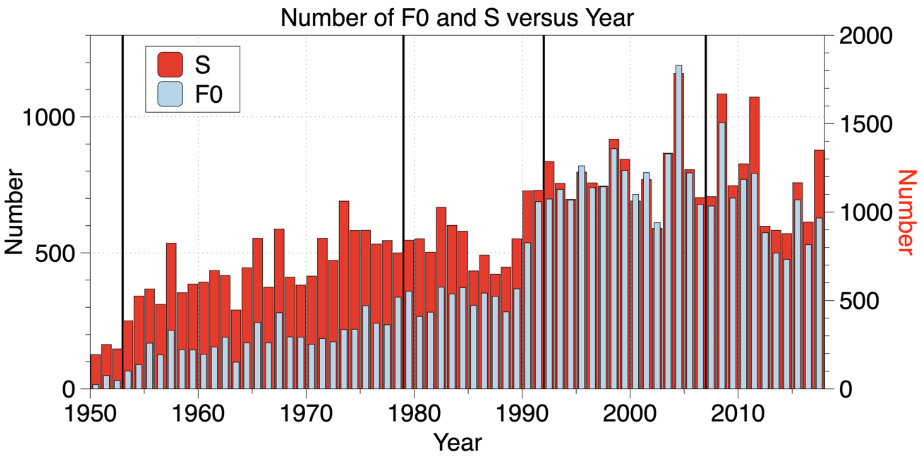


Figure: Linear-linear bar chart of the number of F/EF0 (blue; left axis) and S (red; right axis) tornadoes versus year.

We have added discussion of the possible reasons for the increase in tornadoes with time proposed in prior studies in section 2, paragraph two.

B. *The second part of your question relates to F/EF-scale and whether or not the association between PL and F/EF-scale documented by Kelly et al. (1978; K78) holds with the inclusion of the most recent data. We have...added to Fig. 5 as panel Fig. 5d in the revised manuscript to address this question.*

[Editor's note: Reply figures also added to the paper are omitted from the review notes to save space.]

Section 1: Radar utility (scan length and implied tornado "intensity"): While I certainly agree on imperfect tornado detection and the reasons for not explicitly tracking tornado length with radar, the last three sentences on p. 3 are awkwardly and incompletely stated. For one thing, scans "every 4–6 min" is no longer a fully valid statement in the era of dual-polarization (Bringi and Chandrasekar 2001) capabilities, beginning in November 2010 (NWS 2010); with the Supplemental Adaptive Intra-Volume Low-Level Scan (SAILS; Chrisman 2011) method, in 2014. In addition to estimating motion and PD, radar imagery also can be used to estimate tornado intensity operationally (via association with ranges of windspeeds attached to EF-scale damage ratings—e.g., Smith et al. 2020a,b). The latter may be worth brief mention and citation.

Reviewer C also had concerns related to this discussion. We were naïve with regard to some of the details of more recent radar data technology in neglecting to include reference to the SAILS method (Chrisman 2011; Smith et al. 2020a,b). We have reworded and reduced the discussion on this issue and have added citation to Chrisman (2011) and Smith et al. (2020a,b). [Note that Nixon and Allen (2021) is cited in the discussion of PL reliability.]

Section 1: Day vs. night casualty differences by path-length category: Given the striking difference apparent in the last two panels of Fig. 4, brief discussion of the day/night difference in nocturnal vs. all V tornadoes (or even better, vs. daytime, not shown) would be most interesting and insightful in this part of section 1, particularly in context of the Ashley et al. (2008) findings that you already cite elsewhere. Something clearly is going on with Vs (as normalized by sum of PLs) that is causing a much-greater share of night casualties. Any supportable idea what? To a lesser extent, this also may apply to the S expansion in tornado count-normalized share shown in panel (h), vs. panel (c).

We believe you are referring to the original Fig. 3, which is now Fig. 4 in the revised manuscript. We noticed this too with V tornadoes "sticking out" in some of the parameter spaces, particularly nighttime deaths and injuries divided by the number of tornadoes. However, there is a danger in trying to formulate an explanation with only three nighttime V events (TX, NC, and MS). There are also only three nighttime X tornadoes, however, one is rated F/EF0 (the mean F/EF-scale rating for the 37 nighttime L events was

2.2). Thus, compared to the X events, the three V events, two of which have rating F/EF4 and one of which has rating F/EF3, could be understood to potentially be associated with greater deaths and injuries per tornado (small denominator), and per tornado per PL. Nevertheless, the disproportionate number of deaths and injuries per tornado per PL mile associated with long-track tornadoes is demonstrated by the data in Fig. 4. These points are described in more general terms in the revised manuscript (to avoid listing excessive details—an issue raised by Reviewer C).

<u>Section 2: Statement on tornadic vs. nontornadic mesocyclones</u>: Is it really unknown if mesocyclone cycles differ between tornadic and nontornadic supercells? I'm questioning this statement, just given all the observations of each supercell type in field programs (VORTEX, VORTEX2, etc.), as well as modeling work across the literature over the past few decades that has both succeeded and failed in producing tornadoes from simulated supercells. A little more literature review and affirmation are needed here, if this statement is to be retained.

We have added supporting information from observations that include varying cycle times from Darkow and Roos (1970), Burgess et al. (1982), and from VORTEX (Dowell and Bluestein 2002). Citations to model results include cyclic times from Alderman et al. (1999), Adlerman and Droegemeier (2002); Wicker and Wilhelmson (2006); Gaudet and Cotton (2006); Coffer and Parker 2017; and Markowski (2020). Markowski (2020) who examined the effects of varying the initial PBL perturbations in supercell simulations and found "very limited intrinsic predictability". In a mobile dual-Doppler case study of a nontornadic cyclic supercell, Beck et al. (2006) state that while the mesocyclone cycle times were much shorter (~6 min) than previously studied cyclic cases, there were no obvious dynamic differences between the mesocyclone cycle evolution for their nontornadic storm and tornadic storms. In addition, they cite Trapp 1999; Wakimoto and Cai 2000; Markowski 2002 to support the finding. We have added these citations to our text. Furthermore, several studies from VORTEX-95 showed no obvious differences between mesocyclone evolution in tornadic versus nontornadic supercells (e.g. Blanchard and Straka 1998; Wakimoto et al. 1998; Trapp 1999; Wakimoto and Cai 2000; Markowski 2002; Markowski et al. 2002). We have reworded our sentence to state that observations show no obvious differences between mesocyclone evolution in tornadic versus nontornadic supercells, but that there are some indications that mesocyclones associated with tornadoes might have longer cycles (c.f., ~6 min from Beck et al. 2006 for nontornadic cycles with 44 min from Lee et al. 2012 associated with an F/EF4 tornado and preceded by nontornadic shorter cycles on the order of 7–13 min).

Section 3 onward: Usage of "touchdown" and "touch down" for tornadoes: This term is colloquial slang, physically unsupported and misleading, but appears often in the middle–latter parts of the paper. Tornadoes do not "touch down". Instead the air in them is *rising* at genesis time; if anything, they spin up instead (Houser et al. 2018). Fortunately, shorter and more accurate verbs are available: begin, start, form, etc., so the solution here is easy too. Please change this wording everywhere originally used.

All instances of "touchdown" have been changed to phrases such as "tornadoes formed" or similar wording, as you suggest.

[Minor comments omitted…]

Second Review:

Recommendation: Accept with minor revision.

Overview: The scope and foci of the manuscript remain largely as posited in the initial review round. However, revisions reveal much more streamlined and organized discussion, along with greatly improved writing, more attention to detail where needed, supportive citations for previously unsupported statements, removal or compression of extraneous material, and coverage of several important points missing from the original.

My recommendation is "accept with minor revision". The authors mostly have addressed major, substantive comments from my initial review satisfactorily. Remaining scientific and organizational concerns are relatively minor in nature—and far fewer technical errors appear than in the initial draft. I commend the authors for their obviously substantial and time-consuming work in making many needed improvements at the behest of all three reviewers, collectively. Because so much revision was done, I do have some substantive comments that didn't arise from the initial draft and require attention, but wouldn't categorize their needed disposition as "major" (especially compared to those in the first review). Those follow next.

We thank you for your very helpful comments as reviewer and editor on both versions of the paper. We have addressed all of your second-review comments. Any additional changes to the manuscript that were not requested are described below. With your suggestions and those of the other two reviewers, we believe the paper has been greatly improved.

Summary of changes:

- *New solar hour calculation and nighttime definition changed to sunset–sunrise.*
- *Path-width adjustment changed to apply to three eras (1979–1994, 1995–2006 and 2007–2018), as suggested by the editor.*

In agreement with the reviewers, we have changed the definition of nighttime from 23pm–7am to nighttime determined using precisely calculated sunset and sunrise times. This sunset–sunrise nighttime definition resulted in 7666 tornadoes being added to the nighttime dataset, which also provides an improved nighttime sample size, with a more physical basis. Of these 7666, 7565 were S, 94 were L, 7 were V, and 0 were X (101 LVX) PL category tornadoes. The change in sample size did not change the general conclusions of the study, but there were some changes described next for the reviewers.

The resulting change in sample size associated with the change in the definition of nighttime resulted in more reliable, more physically consistent, less sporadic statistics in many of the parameter spaces. An example of one of the changes that resulted from the change in nighttime definition was that the maximum F/EF scale (Fig. 5b; Fig. 6) of all PL category tornadoes except for X changed by at least one F/EF scale category (ALL and S from F/EF1 to F/EF0; LVX and L from F/EF2 to F/EF3; and V from F/EF4 to F/EF3 [X maximum remained at F/EF4). The coalescence of LVX, L, and V tornadoes, around F/EF 3 seems more consistent. Further, more nighttime LVX occurred in the Midwest (as well as in several additional states, which were added for all PL categories except X) with the new nighttime definition (Figs. 9, 10). An important change was to the nighttime monthly maximums; for ALL and S the maximum month changed from April to May; LVX from November to April and V from a three-month tie to March. The shift of the nighttime tornado frequency maxima to the springtime months also seems more consistent and indicates a more adequate sample size. Although the springtime death and injuries values increased for ALL tornadoes, there were still secondary maxima in November for LVX-, V- and X- tornado-related deaths and injuries.

Substantive scientific comments (in chronological order):

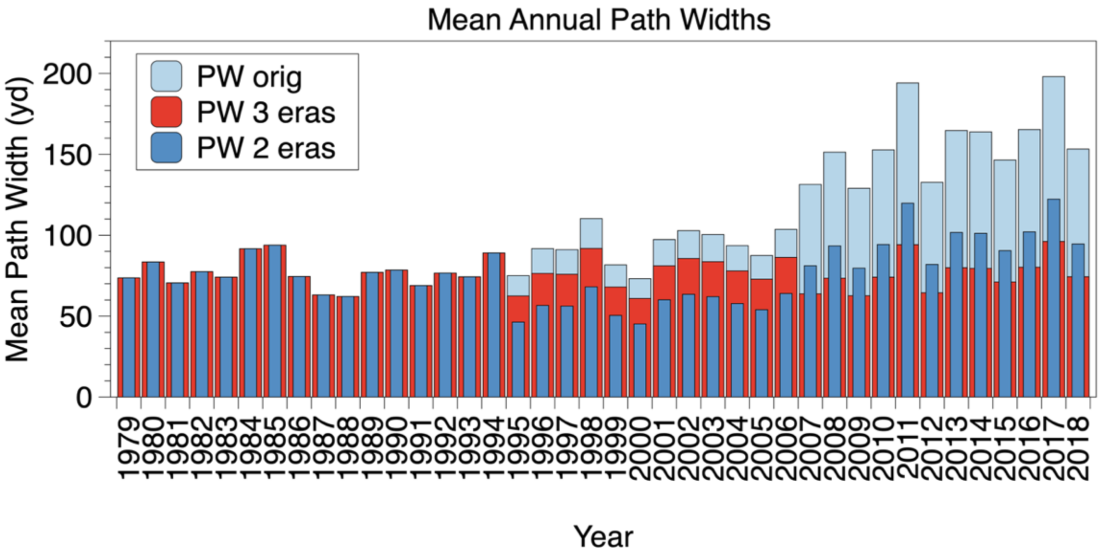
<u>Section 2</u>: Regarding the choice of hours for nighttime, I'm still not sold on this rigid definition of day or night, as it still is less physical than one adjusted to latitudinal and seasonal changes (which the authors rightly acknowledge here, unlike in the first draft). That said, at least it is explained much better, and is somewhat more physical than a definition that would include daylight hours in some latitudes or parts of the year. No one can dispute reasonably that the chosen hours are nighttime in the CONUS. I'll reluctantly agree to this change for now, but have sample-size concerns that the authors should address at least briefly in the text. Also, this issue may need still more attention in response to input yet to arrive from other reviewer(s) as of this writing.

We agree. Please see the summary of changes above for the response to this comment.

As for width, multiplying the 1995+ PWs by a post-"mean width" ratio is a good first step, but not sufficient, in light of the substantial path-width increase EBC21 documented within the 1995+ mean-width era (coincident with the EF scale). How about two normalizations: one for 1995–2006 mean-width part of the F era, and a stronger one for the major 2007+ EF-era path-width jump? Between Agee and Childs' findings and EBC21, this is justified easily.

Note to the Editor: The adjusted PWs were NOT accurately plotted in the figures at the time of the last submission (10/26/21). Figs. 13, 14, 15 and 16 were affected. The error has been rectified and these figures and text description have been corrected, as described next.

The use of three eras to adjust PW was an excellent suggestion. Thank you. Using only two eras (1979–1994 and 1994–2018; figure below, dark blue thin bars), results in too much damping of the PWs from 1994–2006, and not enough damping of the PWs after and including 2007. The use of different "damping" or "adjustment" coefficients for the three eras (1979–1994, 1994–2006; and 2007–2018; red bars), resulted in a more even distribution of annual mean PWs for all the years under consideration, 1979–2018.



Section 4a: The formally published concept of "Fujita miles" (e.g., Fuhrmann et al. 2014) probably should be discussed here at least briefly, since it directly attaches F/EF rating to path length and therefore is relevant to the concepts discussed in this section. For what it's worth, and despite its statistical ease of cross-event comparison, I find post-facto indices such as "Fujita miles" and their related concept of "hectopascal miles" to be overly coarse and potentially misleading for event-ranking purposes. This is because of their highly unphysical, inferential extension of peak point rating (F miles) and implicit power or energy dissipated (hPa miles) to an entire path length, in a computational sense. In fact, peak rating only occupies small parts of even the most violent tornadoes [e.g., the EF5s in Moore surveyed by Marshall (2002) and Burgess et al. (2014)]. Still, it would be somewhat remiss not to acknowledge and relate to those published measures in this work.

We added the suggested references and a comment on this issue to Section 4d.

[Minor comments omitted…]

REVIEWER C (John T. Allen):

Initial Review:

Recommendation: Accept with major revisions.

General Comments: Overall, while there are likely publishable elements to this manuscript, this is not clearly evident from the original submission. The text reads as if it were not appropriately proofread, wanders between topics, elements of literature and conflates results with introduction, data and methods, to the point where is it is almost unreadable. The text could be significantly shortened and streamlined to focus on the most relevant elements, and synthesize the arguments and niche into something that a reader can follow. Furthermore, the use of acronyms is to the point of making the manuscript almost impossible to follow, and is perhaps the most expansive I've ever seen. I very quickly lost track of the acronyms being used and would urge that the authors rethink their usage to ensure that acronyms are used for effect and focus on using them where necessary. Based on these points, and the lack of discussion of how confounding factors may obfuscate the statistical results, I would recommend this paper undergo mandatory major revisions.

Thank you for your helpful and insightful review, which we think has led to improvement in our manuscript.

We agree that the manuscript could be organized in a more sequential. We have rewritten and reorganized sections 1-3 completely and restricted presentation of results to section 4. [Editor's note: Long-form outlines presented in the reply are omitted since organization is apparent from the manuscript.]

General Comment Responses Summary:

- *We have substantially reorganized the paper.*
- *We have removed essentially all acronyms except those listed above and included a Glossary for those retained.*
- *We have made every possible effort to comprehensively proofread the revised manuscript. We thank all the reviewers for pointing out technical issues.*
- *In regard to your comment in your opening paragraph on "confounding factors" or limitations: Limitations were originally stated in the submitted paper, but are discussed in more detail with more supporting citations in the new section 2 (Data and methods), with the introduction of, changes to, and limitations of, the severe weather database. Limitations are also pointed out throughout the paper where they might impact interpretation of the results and are then summarized in section 5, Summary and conclusions.*

Major Comments: The introduction needs significant work, and does not take into account sufficient survey of existing studies or do so in a way that is followable for the reader. There is little detail of the concept as to why this study is being conducted, or the purpose of the work—it is pretty much straight down to business in the first few pages—only to wander back to relevant studies several pages in. By halfway through the second paragraph, the authors start describing methodology/results—and yet continue with the introduction somewhere near the end of page 5. Where new studies are introduced, this is done in a long-winded manner, that doesn't sufficiently synthesize the information and instead just states large elements of the content. To make this manuscript acceptable, this issue needs to be addressed. For example, at times references seem to lack citations to relevant studies, regarding tornado associated deaths, or other aspects of tornado paths (e.g. width, intensity) and building a synthesis as to what is being addressed. The authors also do not mention whether the long-term statistics of path length can be believed—Harold Brooks in a number of presentations, in Brooks (2004) and discussions has highlighted that path length extended through time, certainly as we moved into the Doppler radar period – other studies such as Zenoble and Peterson (2017) raise significant questions about believability. Add to this the effect of interannual variability and outliers, and the details of the results become somewhat questionable given sample size. For the authors' benefit I've included several references that seemed to me either not or missed in their citation during relevant content.

We have made every effort to more comprehensively cite the relevant literature on tornado path length and width, deaths and injuries, and tornado damage ratings where appropriate in the text. We have added those references you and the other Reviewers have suggested that were not cited in the original submission (e.g., Ashley 2007; Zenoble and Peterson 2017, thank you for bringing this study to our attention; Garner et al. (2021), was not available at submission time; Nixon and Allen (2021), thank you for bringing this recent study to our attention). Regarding path width in particular, we have added a new Subsection 4c to address the concerns of Reviewer B.

Your statement, "The authors also do not mention whether the long-term statistics of path length can be believed" is very important.

We did address this issue in the originally submitted manuscript in the original section 3. We also attempted a cursory quantification of some PL discrepancies and presented this in the originally submitted manuscript. However, we have attempted to make discussion of PL reliability more concise and have positioned the discussion in section 2, where the database limitations are described. The discussion includes further citations (with suggestions from reviewers included).

Specifically, we point out that some tornadoes reported as having continuous PLs were also reported as "skipping" tornadoes, or that some were actually families of tornadoes. We include the discussion of the possible PL discrepancies found from comparing the reported PLs with those calculated using the provided starting and ending latitude and longitudes and we point out a couple of specific questionable LVX tornado cases. We believe the new discussion of path length reliability is more comprehensive and that limitations are more strongly stated and supported in the revised manuscript.

For a relatively limited sample size, there is excessive description and analysis of every single detail and minutia of the results, which could easily be streamlined to focus on the most relevant or significant results in the context of existing literature while mentioning others as not shown. This streamlining would also likely abate the need for the deluge of acronyms as an added benefit. *[Editor's note: This also might reduce the number of figures by a few, which would be a good thing, as they are around the upper bounds for an acceptable manuscript.]*

These are very good points, some of which were also raised by the other reviewers. In many cases, rather than listing specific numerical values and relationships, more general interpretations are offered. Note to the reviewer and editor: The original Fig. 22 was removed completely; however, three figures were added in the new subsection 4c to address the concerns of reviewer B (editor) regarding path width.

<u>Conclusions and neglect of limitations</u>: There is already pre-existing work that begins to explore the environments of long-track tornadoes, see Garner et al. (2021). There is also no discussion of the significant role that interannual variability and outliers play in the statistics here – for example the 2011 outlier plays a significant role in the determination of the April peak, yet not mention is made of this as a potential confounding factor. Such a discussion is necessary in the context of a study like this.

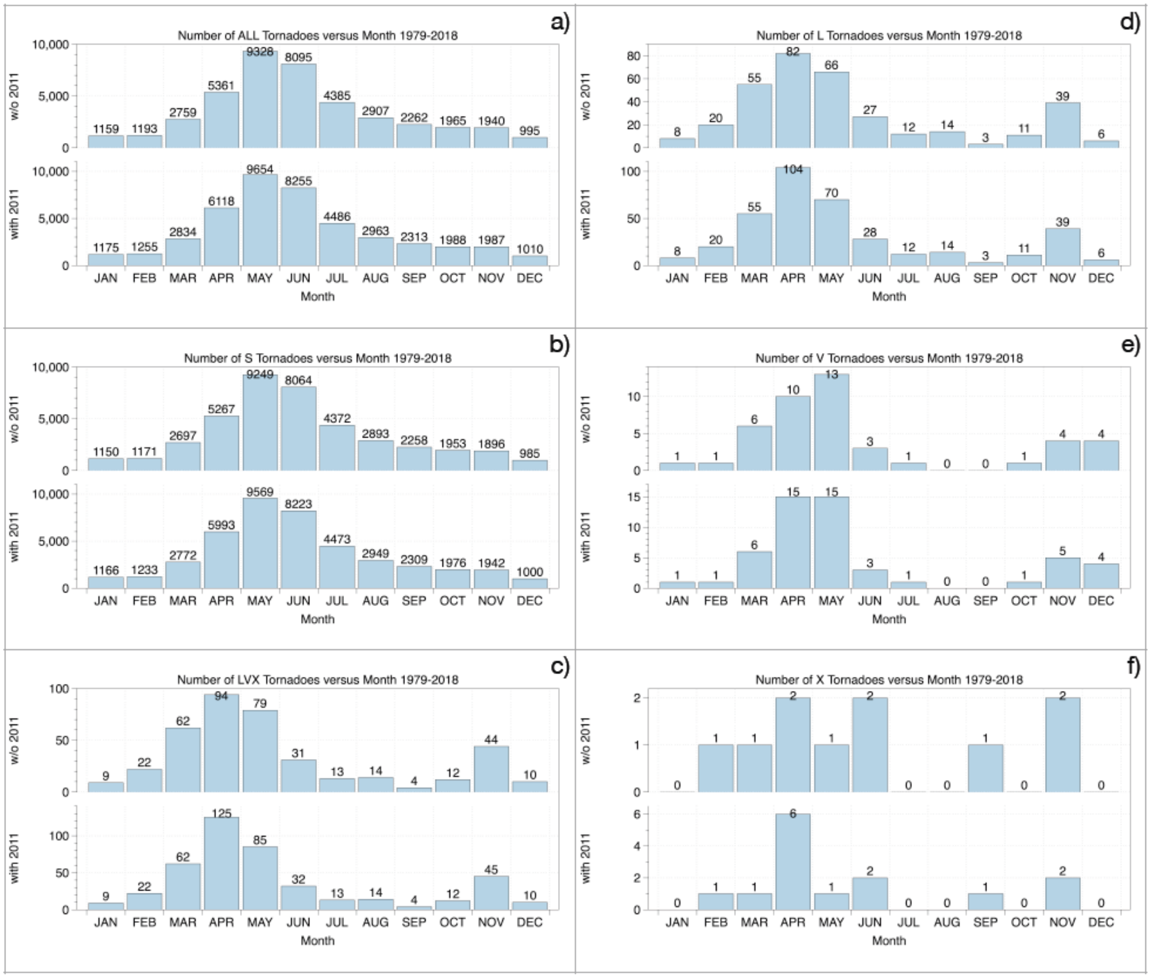
Several limitations were stated and restated in the conclusions in the originally submitted paper. However, as stated above, we consolidated and expanded these in the description of the dataset, where appropriate in presentation of the results, and finally in paragraph two and three of the summary and conclusions section. We did not have access to Garner et al. (2021) when we submitted the paper, but have included reference to this new work throughout the paper where appropriate as G21. We discuss the findings of G21 related to PL and PW, in section 3, 4c and 4e. One limitation of G21 is the small number of years considered (six years from 2009–2015). The environments of long-track tornadoes (extending/complementing the work of G21) will be explored in future work.

Your comment, "Significant role that interannual variability and outliers play on the statistics": Specifically, what is the influence of 2011 peak on the preferred month of April?

This is an excellent point. Thank you. To address this, we examined the data with and without 2011 tornadoes included to see whether or not the preferred month was changed.

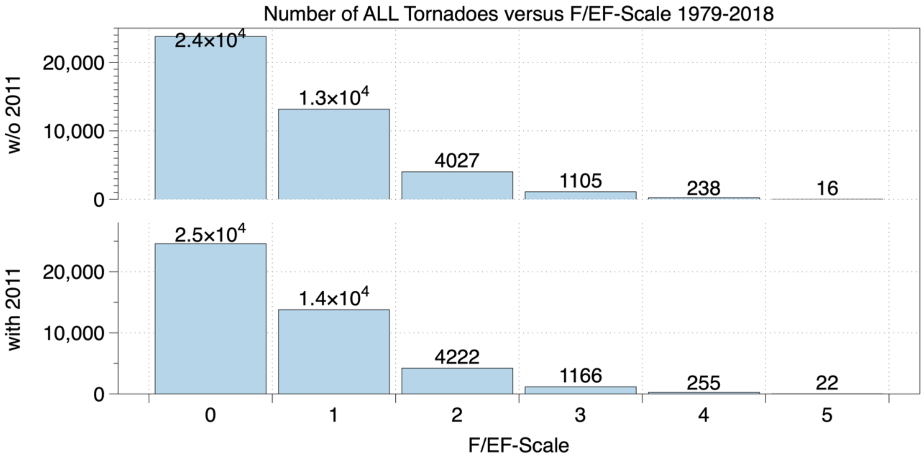
We provide the (following) figure for this response to the Reviewer, however, we did not add this figure to the manuscript. We did include findings based on the data in this figure in the text in section 4e of the manuscript.

We found that removal of the 2011 tornadoes from the dataset did not change April from the most prominent month for LVX tornadoes. The 39 LVX tornadoes in 2011 is ~50% larger than the next largest number, 19, which occurred in 2008. However, the removal of 2011 tornadoes resulted in a May maximum for V tornadoes rather than the tie that existed between April and May with 2011 tornadoes included. These impacts of 2011 cases on the monthly statistics are discussed in section 4e.



<u>Figure</u>: Linear-linear charts of the number of tornadoes versus month, with and without the tornadoes of 2011. a) ALL b) S; c) LVX; d) L; e) V; and f) X.

Moreover, removal of the 2011 cases also did not change the F/EF-scale statistics appreciably (figure below is not included in the paper, but just in this response to the Reviewer).



<u>Figure</u>: Linear-linear bar charts of the number of tornadoes versus F/EF-scale with (bottom) and without (top) the tornadoes of 2011.

Lastly, the large number (of) 2011 tornadic events is now discussed in section 3.

[Minor comments omitted…]

Second Review:

Recommendation: Accept with minor revisions.

Synopsis: The authors have done a nice job of revising the manuscript, and I certainly appreciate their extensive efforts. In my view, it provides a comprehensive timely reference to the statistical properties of path lengths, motion and duration (which would have been useful in recent weeks). I also do like the revised clarity regarding the choice to define path length based on relationships to the forward progression speed and duration, rather than just the resulting path. There are still a few parts of the manuscript that need revision, but overall I feel that the paper will make a solid contribution to the literature. Accordingly, I recommend a set of minor revisions.

We thank you very much for your continued comprehensive, thought-provoking and insightful reviews that we believe have led to a much-improved manuscript. We have addressed all your comments positively and thank you for all your helpful recommendations.

[Editor's note: A couple of comments and replies appeared substantive enough to include below on the review record. A "Summary of Changes" that was given in the reply to Reviewer C is the same as found in the response to Reviewer B, and can be read there.]

P. 1: "Unfortunately, an analogous, physical evidence- or statistical-based scale describing long-track tornadoes does not exist, nor does one exist for tornado longevity."

I would be curious as to what would be the point of such a scale, given that we can use GPS to identify the path proportions of tornadoes already and state these values?

Argument for using a PL scale:

You make an interesting point. In the same vein, at least in part, one could ask what would be the point of the EF scale if the damage could be estimated using the winds from radar? Physical and conceptual categorizations are used ubiquitously in science and societal matters. A common example is astronomical, nautical, and civil, sunset and sunrise. Further, doctors use low-, normal-, and high-birth weights and lengths for guidance on infant nutrition and care. They also use body weight and height to determine a Body-Mass Index (BMI) and scale to estimate whether a person is underweight, ideal-weight, overweight, or obese to help establish healthcare. Meteorological scales help forecasters inform the public of impending potential dangers. Just like mariners use/used the Beaufort Scale to characterize winds from calm to hurricane-strength, along with expected sea heights in terms of ranges and physical characteristics, hurricane forecasters discuss hurricane wind speeds, pressure, and storm surges in terms of very dangerous, extremely dangerous, devastating and catastrophic. In addition, tornado forecasters discuss tornadoes as weak, strong, and violent to categorize damage. Similarly, PL information regarding long-, very long and extremely long path-length tornadoes can be used to indicate expectations of physical characteristics and potential dangers to property and life. Historically, Fujita and Pearson developed the FPP scale to estimate the characteristics of tornadoes by the damage they do, as well as path length and path width scales, for situations, for example, when the NWS could not conduct extensive damage surveys. The F scale gained the most notoriety of these three components of the FPP scale, however, all three measures are reported in Storm Data. Nevertheless, length and width of tornado tracks (as well as their duration and forward speed) are important attributes as they can provide some insight into the qualitative state of the atmosphere and the nature of storms in which they formed. A historical record of this information is essential to those studying the formation, maintenance and demise of tornadoes.

As noted in the previous review response, an example of research which used PL to help to understand tornadic storm dynamics is Dowell and Bluestein (2002), of a family of tornadic storms, the last of which *was very strong, as well as long-lived/longer-tracked. The study of their long-track cyclic supercell provided guidance in how to interpret low-level and mid-level dynamics in the tornadic storm which the tornado family formed, and how the change in the storm behavior resulted in it producing an early series of weaker and shorter-track tornadoes to a later powerful long-lived tornado. In their case, the long-lived tornado in their study had a path-length that was a couple of standard deviations from the median from the other tornadoes the storm produced. In other words, the observed PL of the early short-track tornadoes, followed by the observed PL of the long-track tornado from the same supercell storm, provided evidence of the dynamic change in storm morphology from cyclic supercell to non-cyclic supercell. The study of Dowell and Bluestein (2002) also shows the climatology of the tornado PLs for research scientists and forecasters can/could be quite useful. With regard to tornado PLs, research has suggested that longer-lived, longer-tracked, and wider tornadoes tend to cause more damage, and deaths and injuries. In the current study, we show tornadoes with the longest PLs tend to produce far more deaths and injuries per tornado, PL mile, than intermediate-long-track or short-track tornadoes, even when comparing long-track to violent short-track tornadoes. Scales provide a basis for expectation and both physically-based and statistically-based methodologies can be used, each with their own set of limitations, in research and practical use. We state in our conclusion section that more path-length stratification thresholds, based solidly on statistics and/or dynamics (rather than unknown factors), should be explored more thoroughly.*

P. 3: "To help quantify uncertainties and detect issues with tornado PLs ≥30 mi (48.3 km) in the database, the difference between the reported lengths in miles and the distance calculated for cases with known beginning and ending latitude and longitude was calculated." I have several reservations as to whether this argument is a reasonable choice. We know that in practice tornado tracks are often arced or curved, whereas the data stating the start and end of the part are the shortest distance between two points. On this basis, can we be sure that all NWS offices follow the same procedure in assigning path length? It is likely while there are some differences where there were errors in entry, the authors haven't identified questionable paths, but in some cases may be just paths where a tornado deviated from a linear path, and the flaws of the storm date recording mechanism based on start and end point are being revealed. I feel that this must be noted as a caveat in the discussion here, and noting that it might not be that the paths are wrong. I know the authors do mention this point on p. 8, but it feels appropriate given this is leading to a decision of filtering.

We generally agree with all your points on this issue. This approach was used only as a first-pass attempt to find gross errors. We actually used distance differences of 1, 2, 4, 8, 32 and 64 mi (1.6, 3.2, 6.4, 12.8, 25.6, and 51.2 km) as well as a list of percent differences. In checking all V and X tornadoes, it turned out that all of the cases with known starting and ending latitude and longitude in the SPC database (supplemented with information from NCEI Storm Data) that proved to have inconsistencies were identified using a difference >4 mi. This approach cannot account for curved or irregular paths and certainly was not meant to find all errors as it is based, in part, on point-to-point calculations, as you noted. The issue you raised is now addressed in the paper with a more precise statement of intent and limitations. Please note: regarding your comment, "but it feels appropriate given this is leading to a decision of filtering.": We have not filtered the dataset based on this cursory analysis. The analysis was only an effort to outline one of the limitations of the PL data. We now have stated this in the text.

[Minor comments omitted…]