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ORIGINAL PAPER

Tornadoes in the USA are concentrating on fewer days, but their power dissipation is not

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Abstract
The Gini coefficient, Palma ratio, and the ratio of the percentage of tornadoes occurring on days with 20+ tornadoes to the percentage of tornadoes occurring on days with 1–9 tornadoes were used to measure the concentration of tornadoes in the USA for each year over the period 1954–2017. The Gini coefficient and Palma ratio were also used to measure the concentration of tornado power. All three metrics illustrate that most tornadoes are concentrated on relatively few days and that power is even more concentrated. Trend tests illustrate that tornadoes are becoming more concentrated over time, but the power dissipated by tornadoes is becoming less concentrated. Despite the declining trend, most of the power dissipated by tornadoes remains highly concentrated on relatively few days.

1 Introduction

Tornadoes are among the deadliest severe convective weather hazards in the USA. They caused a total of 19,452 fatalities from 1808 to 2017 (Agee and Taylor 2019). The number of fatalities per year was stable across the early-to-mid decades within this period (e.g., 1880–1949) but has declined across the most recent decades (e.g., 1950–2005) (Ashley 2007; Fricker et al. 2017). Despite this decline, tornadoes are still a notable hazard, as they were responsible for an average of 69 deaths per year over the most recent 10 years of record, 2009–2018 (NWS 2019).

The number of fatalities and injuries (i.e., casualties) a tornado produces depends on complex interactions between the geophysical attributes of the tornado, the socio-economics and demographics of the affected population, and the built environment (Boruff et al. 2003; Merrell et al. 2005; Ashley 2007; Ashley et al. 2008; Sutter and Simmons 2010; Simmons and Sutter 2011; Dixon and Moore 2012; Ashley and Strader 2016; Strader et al. 2016, 2017a and b; Fricker et al. 2017; Elsner et al. 2018; Strader and Ashley 2018). Important geophysical attributes include the estimated intensity and energy dissipation, or power, of a tornado. Tornadoes with higher damage ratings (e.g., strong and violent (E)F2–(E)F5) yield more casualties than do tornadoes with lower ratings (e.g., weak (E)F0–(E)F1) (Merrell et al. 2005; Ashley 2007; Simmons and Sutter 2011). Tornadoes that dissipate more energy (i.e., those with greater power) also tend to yield greater casualty counts (Fricker et al. 2017; Elsner et al. 2018; Fricker and Elsner 2019).

The number of casualties is also positively related with tornado outbreak metrics (Fuhrmann et al. 2014), meaning that casualty counts tend to be greater with outbreaks of more tornadoes. Tornado activity in the USA is trending toward larger outbreaks. Increases over time in the number of outbreaks (6+ tornadoes with no longer than 6 h between successive tornadoes) per year with many tornadoes (Tippett et al. 2016), the percentage of annual tornadoes occurring in outbreaks (Fuhrmann et al. 2014; Tippett and Cohen 2016), and the mean number of tornadoes per outbreak (Tippett and Cohen 2016) illustrate this trend. Also illustrating this trend are the decreases and increases in the number of days per year with few and many tornadoes, respectively (Brooks et al. 2014; Elsner et al. 2015; Moore 2017, 2018; Moore and DeBoer 2019). These concurrent and opposite trends have led to increases in the percentage of annual tornadoes occurring on days with multiple tornadoes (Elsner et al. 2015) and in the mean number of tornadoes per tornado day (i.e., a day with 1+ tornado) (Moore 2017, 2018).

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Multiple lines of evidence suggest that tornadoes are concentrating on fewer days. It has also been shown that tornado power has increased over the past few decades (Elsner et al. 2019), but the concentration of power has not been quantified or assessed for trends. We build on these previous efforts by using the Gini coefficient, Palma ratio, and the ratio of the percentage of tornadoes occurring on days with 20+ tornadoes to the percentage occurring on days with 1–9 tornadoes (i.e., the 20+/1–9 ratio) as measures of the concentration of tornadoes and tornado power in the USA. Applied to tornado counts, these measures will complement previous efforts to quantify the increased concentration of tornadoes. Applied to power, these measures will illustrate how concentrated the power of tornadoes is across the days in a year.

2 Data and methods

The Storm Prediction Center provides data for tornadoes that occurred in the USA and its territories between 1950 and 2017 (SPC 2019). In this study, we work with the subset of 32 354 (E)F1+ tornadoes (i.e., tornadoes rated 1 or higher by the Fujita or Enhanced Fujita ((E)F) damage scales) that occurred in the contiguous USA over the period 1954–2017. Removal of the first 3 years and (E)F0s eliminates the increasing trend across the record that is related mostly to changes in detection and reporting practices over time (Verbout et al. 2006; Kunkel et al. 2013; Agee and Childs 2014). This subset is also consistent with other studies that evaluated temporal trends in tornado outbreaks and tornado days (i.e., days with 1 or more tornadoes) (Brooks et al. 2014; Fuhrmann et al. 2014; Elsner et al. 2015; Tippett and Cohen 2016; Tippett et al. 2015; Moore 2017, 2018; Moore and DeBoer 2019).

The destructive potential of tornadoes can be linked to the amount of energy dissipated, or power, at the surface. We calculate tornado power (P) using the equation defined in Fricker et al. (2017) and Elsner et al. (2018) as

$$P = A_p \rho \sum_{j=0}^{5} w_j v_j^3 \tag{1}$$

where A_p is the area of the approximate path, ρ is air density (1 kg/m^3), v_j is the midpoint wind speed for each damage rating j, and w_j is the corresponding fraction of path area by damage rating. Path area exists as the product of the recorded path length and path width, while fractions of path area by damage rating are consistent with recommendations made by the U.S. Nuclear Regulatory Commission (Fricker and Elsner 2015), which combines a Rankine vortex with empirical estimates of post-storm surveys (Ramsdell Jr and Rishel 2007). Path width exists as a mean value before 1995 and a maximum value after. Like Agee and Childs (2014), here we adjust the values using the diameter of a polygon to calculate mean values of width after 1995. Unlike other measures of tornado intensity (e.g. Destructive Potential Index (DPI) (Thompson and Vescio 1998), tornado power is an extensive variable, which can be summed over time and across space.

We used three metrics to measure the concentration of tornadoes: the Gini coefficient, the Palma ratio, and the 20+/1–9 ratio. We used only the Gini coefficient and Palma ratio to measure the concentration of tornado power. These metrics were applied to time series of tornado day magnitudes (i.e., the number of tornadoes on a given convective day (12–12 UTC)) and accumulated tornado power (Schroder and Elsner 2019) on tornado days (i.e., summation of tornado power for all (E)F1+ tornadoes on a given day).

The Gini coefficient measures the degree of uniformity of a distribution and ranges from 0 (uniform) to 1 (non-uniform). It was initially designed as a measure of the distribution of wealth but has recently been applied in the field of climatology because it is insensitive to scale or probability distribution, and it is easy to interpret (Masaki et al. 2014; Rajah et al. 2014; Sun et al. 2015; Konapala et al. 2017; Sun et al. 2017; Pendergrass and Knutti 2018; Sangüesa et al. 2018). The Gini coefficient (G) is equivalent to

$$G = \frac{1}{n}\left(n + 1 - 2\left(\frac{\sum_{i=1}^{n}(n+1-i)y_i}{\sum_{i=1}^{n} y_i}\right)\right) \tag{2}$$

where y_i is daily tornado count or daily accumulated tornado power and n is the number of days or tornado days across the period of record, the number of days in a year, or the number of tornado days in a year, depending on the analysis (i.e., the Gini coefficient was computed for tornado counts and power across the entire period of record and for each year of the record, using all days and only tornado days) (Konapala et al. 2017; Sun et al. 2017). As used herein, the Gini coefficient represents the uniformity of the distribution of tornado counts and power across the days (or tornado days) in a given year and across the entire period of record. A coefficient of 0 indicates that the tornadoes and associated power are evenly distributed across all days (or tornado days), whereas a coefficient of 1 indicates that all tornadoes and associated tornado power are concentrated on only one day. The Gini coefficient was computed with the *reldist* package in R (Hancock and Morris 1999; Hancock 2016).

The Gini coefficient is more sensitive to changes in the middle of the distribution than to changes in the extremes of the distribution (Palma 2011; Cobhan and Sumner 2013; Cobham et al. 2016). Moore (2017) and Moore and DeBoer (2019) show that days with few tornadoes (e.g., 1–9 tornadoes) are becoming less common and days with many (e.g., 20+ tornadoes) are becoming more common, but days in the middle of the distribution (e.g., 10–19 tornadoes) are not trending up or down. Because the changes in tornado days are occurring in the tails of the frequency distribution, we wanted to also apply a metric that is more sensitive to changes in the extremes. Like the Gini coefficient, the Palma ratio was designed as a measure of the distribution of wealth, but it was also designed to better-capture changes in extremes where the Gini coefficient is relatively insensitive (Palma 2011; Cobham and Sumner 2013; Cobham et al. 2016). The Palma ratio is defined as the ratio of the share of the gross national income held by the top 10% of the population to the share held by the bottom 40% (Cobham et al. 2016). As used herein, the Palma ratio for tornado counts is equal to P_{90P}/P_{40P}, where P_{90P} is the proportion of annual tornadoes that occur on the top 10% of tornado days (i.e., days with many tornadoes) and P_{40P} is the proportion of annual tornadoes that occur on the bottom 40% of tornado days (i.e., days with few tornadoes). The 90th and 40th percentiles were computed using tornado days rather than all days because the 40th percentile is usually 0 tornadoes per day when including days with no tornadoes (see Fig. 1a). Values < 1 indicate that a greater percentage of annual tornadoes occur on the bottom 40% of tornado days (based on daily tornado count) and values > 1 indicate that a greater percentage occurs on the top 10% of tornado days (based on daily tornado count). Applied to tornado power, values > 1 of the Palma ratio indicate that a greater percentage of annually accumulated tornado energy occurs on the top 10% of tornado days (based on daily accumulated power) and values < 1 indicate that a greater percentage occurs on the bottom 40% of tornado days (based on daily accumulated power).

For tornado counts, we also used a ratio specifically designed for observed changes occurring to the frequency distribution of tornado day magnitude. The 20+/1–9 ratio is the ratio of the percentage of annual tornadoes that occur on days with 20+ (E)F1+ tornadoes to the percentage occurring on days with 1–9 (E)F1+ tornadoes and is intended to capture the changes reported in Moore and DeBoer (2019). Values less than 1 indicate that a greater percentage of annual tornadoes occur on days with 1–9 tornadoes, and values greater than 1 indicate that a greater percentage occur on days with 20+ tornadoes. This ratio was not applied to power.

The Gini coefficient, Palma ratio, and 20+/1–9 ratio were computed for tornado counts and power for each year between 1954 and 2017 inclusive and for the whole period of record. Trends were statistically assessed with the non-parametric Mann-Kendall trend test (Mann 1945; Kendall 1970), where the test statistic (S) is given as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(X_a - X_b) \tag{3}$$

where X_a and X_b are sequential values in years a and b, n is the number of years, and

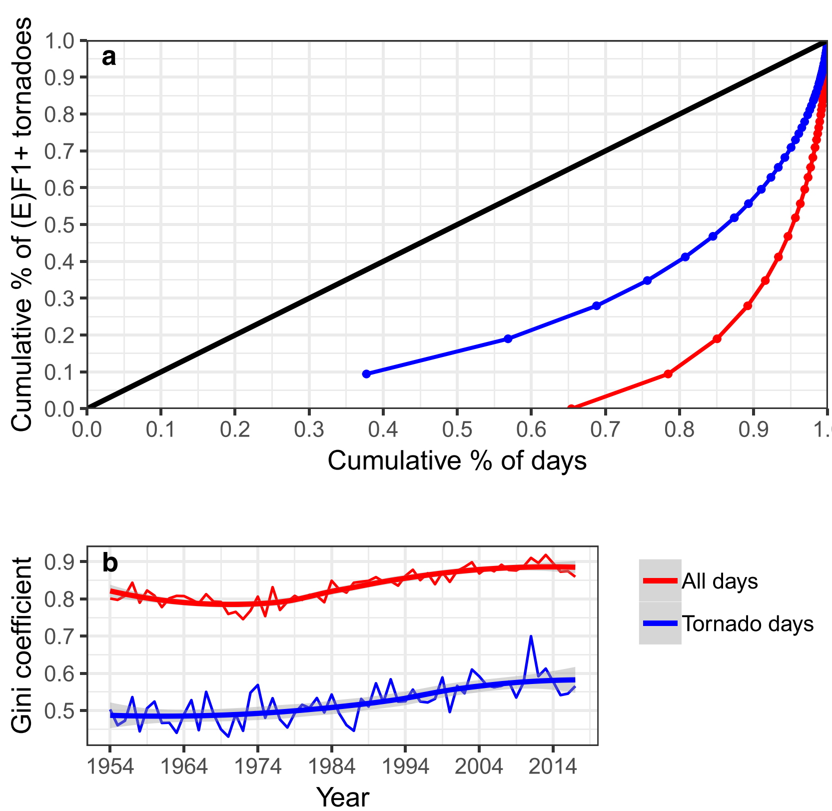

Fig. 1 **a** Lorenz curves showing the cumulative distribution of tornadoes across the cumulative distribution of days, for all days and tornado days (i.e., days with 1 or more (E)F1+ tornadoes). Diagonal black line in **a** shows the line of equality on which tornadoes are hypothetically distributed equally across all days. **b** Annual Gini coefficients for all days and tornado days between 1954 and 2017. Local regression curves (loess) along with 95% confidence interval (CI) are shown in **b**. Trend statistics and significance values are provided in Table 1

$$\operatorname{sgn}(X_a - X_b) = \begin{cases} +1 \text{ for } X_a > X_b \\ 0 \text{ for } X_a = X_b \\ -1 \text{ for } X_a < X_b \end{cases} \quad (4)$$

The linear change over time (β) was estimated with the non-parametric Theil-Sen procedure (Theil 1950; Sen 1968)

$$\beta = \text{Median}\left[\frac{X_a - X_b}{a - b}\right] \text{for all } a < b \quad (5)$$

These procedures are insensitive to the underlying probability distribution, and both have been recently used to identify trends in tornado activity (Gensini and Brooks 2018; Moore 2017, 2018; Moore and DeBoer 2019). Both procedures were completed with the *trend* package in R (Pohlert 2018).

3 Results and discussion

3.1 Trends in the concentration of tornadoes over time

The Gini coefficient for all days over the period of record (1954–2017) is 0.84, which indicates that tornadoes are highly concentrated. The Lorenz curve in Fig. 1a shows that tornadoes did not occur on approximately 65% of the days in the study period. Figure 1a also shows that more than 70% of the observed tornadoes occurred on just the top 10% of tornado days. Because of the large number of days without tornadoes, the Gini coefficient for the period of record decreases to 0.54 when considering only tornado days, which indicates that tornadoes are still concentrated in time when considering tornado days, as more than half of the tornadoes occurred on just the top 10% of tornado days. Neither series of Gini coefficients are stable across the period of record (Fig. 1b). The average Gini coefficient for all days increased from 0.79 to 0.88 from the early (1954–1973) to late (1998–2017) 20-year period. The average Gini coefficient for tornado days increased from 0.48 to 0.57 between these same periods. The increasing trends are statistically significant (Table 1).

The 90th percentile tornado day increased in magnitude over time, from an average of 7.8 tornadoes per day in the first 20 years of the record to 11.5 tornadoes per day in the last 20 years. The 40th percentile tornado day remained stable over time, generally between 1 and 2 tornadoes per day. The percentage of annual tornadoes that occurred on or above 90th percentile tornado day ranged from 0.35 to 0.63, but with a notable increase across the record (Fig. 2a). The percentage of annual tornadoes that occurred on or below 40th percentile tornado day ranged from 0.08 to 0.30 and decreased over time (Fig. 2a). The increasing and decreasing percentages of annual tornadoes occurring on or above 90th percentile tornado day and on or below 40th percentile tornado day led to a statistically significant increase in the Palma ratio over time (Fig. 2b; Table 1). The average Palma ratio increased from 2.4 to 3.9 from in the first to last 20-year period of the record. Therefore, between 1998 and 2017, an average of nearly 4 times as many tornadoes in a given year occurred on just the top 10% of tornado days as compared with the bottom 40% of tornado days.

Table 1 Mann-Kendall test statistic (S), Theil-Sen slope estimates (β), and significance levels (p)

	S	β (year^{-1})	p
Tornadoes			
Gini coefficient (all days)	1248	0.0019	< 0.001
Gini coefficient (tornado days)	1014	0.0018	< 0.001
Palma ratio	742	0.0297	< 0.001
20+/1–9 ratio	894	0.0079	< 0.001
Power dissipation			
Gini coefficient	− 468	− 0.0007	0.007
Palma ratio	− 946	− 9.2623	< 0.001

The numbers of days per year on which 1–9 and 20+ (E)F1+ tornadoes occurred decreased and increased over time, respectively (Moore and DeBoer 2019). The percentages of annual (E)F1+ tornadoes occurring on days with 1–9 and 20+ (E)F1+ tornadoes have likewise decreased and increased over time, respectively (Fig. 3a). Through the 1950s, 1960s, and 1970s, the percentage of tornadoes occurring on days with 1–9 tornadoes averaged 0.69 and ranged from 0.46 to 0.85. The percentage of tornadoes occurring on days with 20+ tornadoes averaged 0.11 and ranged from 0 to 0.25 over the same decades. Since 2000, however, the average percentage of tornadoes occurring on days with 1–9 tornadoes dropped 20 percentage points to 0.49, whereas the average percentage occurring on days with 20+ rose 18 percentage points to 0.29. Because of these opposing changes, the 20+/1–9 ratio significantly increased over time, with the most notable increase beginning in the mid-1980s (Fig. 3b; Table 1). The 20+/1–9 ratio was < 1 in all years but one, which shows that more tornadoes occur on days with 1–9 tornadoes than on days with 20+ in most years. The year in which the 20+/1–9 ratio was > 1 is 2011 (when it was 2.3), when 889 (E)F1+ tornadoes occurred, 584 (66%) of which occurred on days with 20+.

3.2 Trends in the concentration of tornado power over time

The Gini coefficient and Palma ratio for tornado power were computed using only tornado days because of the large number of days with no tornadoes and therefore no power. With a Gini coefficient across the period of record of 0.91, tornado power is more concentrated than tornado counts (Gini

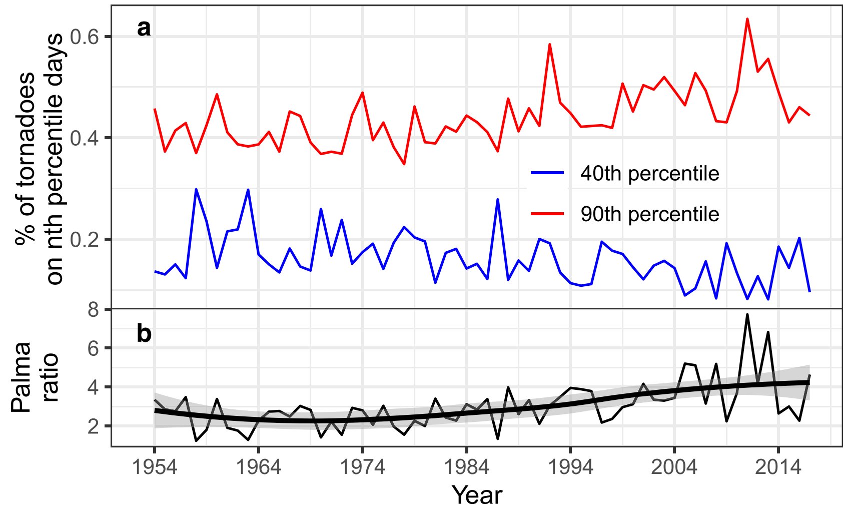

Fig. 2 **a** Annual percentages of (E)1+ tornadoes occurring on or above 90th percentile and on or below 40th percentile tornado days between 1954 and 2017. The 90th percentile/40th percentile ratio, or the Palma ratio, is shown in **b**. A local regression curve (loess) and the 95% CI are shown in **b**. The trend statistic and significance value are provided in Table 1

coefficient = 0.54). The Lorenz curve in Fig. 4a shows that approximately 85% of the power dissipated over the period of record occurred on just the top 10% of the days in this period with the most daily accumulated tornado power. The Palma ratio computed across the period of record of 488.83 also illustrates the concentration of power. This implies that the share of the total power dissipated by tornadoes between 1954 and 2017 that occurred on the top 10% tornado days (i.e., those with the greatest power) is 488.83 times greater than the share that occurred on the bottom 40% tornado days (i.e., those days with the least power).

The annual Gini coefficient and Palma ratio decreased between 1954 and 2017, most notably at the end of the record. The average Gini coefficient was 0.90 during the earliest 20 years of the record and 0.86 during the last 20-year period (Fig 4b). The Palma ratio decreased more notably than the Gini coefficient, from 707.94 to 240.24 between the first and last 20-year periods (Fig. 5c). The average percentage of annually accumulated tornado power occurring on the top 10% tornado days decreased slightly from 0.85 to 0.81 between the first and last 20-year periods, whereas the percentage occurring on the bottom 40% tornado days increased from 0.002 to 0.005 (Fig. 5a, b). Therefore, the increasing percentage of annually accumulated tornado power occurring on the bottom 40% tornado days, rather than a decrease in the percentage occurring on the top 10% tornado days, is the main driver of the decrease seen in the Palma ratio. As seen with tornado counts, the decreases seen in the Gini coefficient and Palma ratio are statistically significant (Table 1). Note that, even with these declines, annually accumulated tornado power is still highly concentrated, with the majority occurring on the top 10% of tornado days.

3.3 Implications of trends

Casualty counts tend to be higher on days with larger numbers of tornadoes (Fig. 6a). The Spearman's *rho* rank correlation between tornado day magnitude and daily casualty count is a moderate, but significant, 0.54 ($p < 0.001$). This relationship is

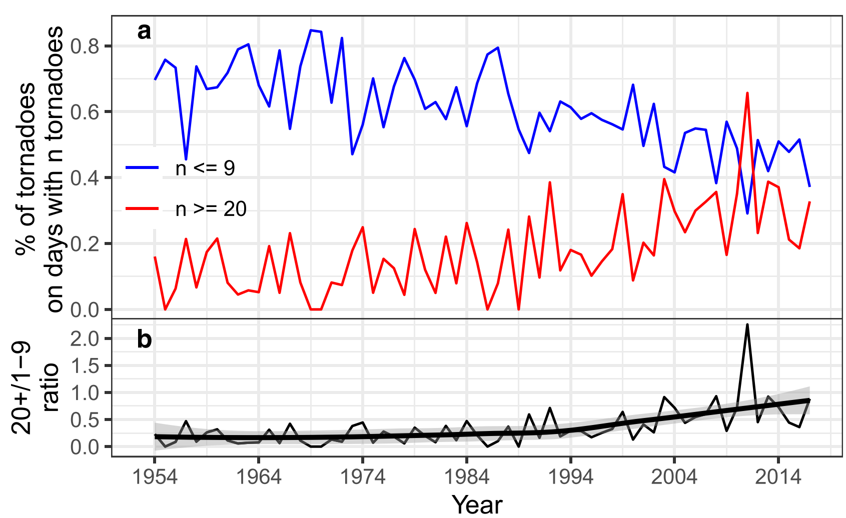

Fig. 3 **a** Annual percentages of (E)F1+ tornadoes occurring on days with 20+ tornadoes and 1–9 tornadoes between 1954 and 2017. The 20+/1–9 ratio along with a local regression curve (loess) and its 95% CI are shown in **b**. The trend statistic and significance value are provided in Table 1

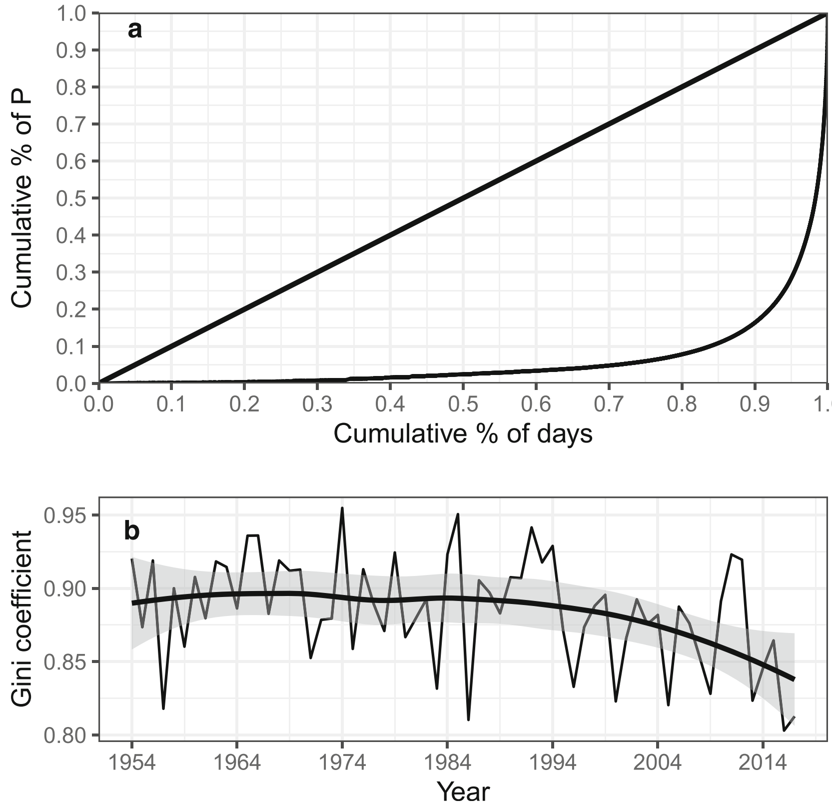

Fig. 4 **a** Lorenz curves showing the cumulative distribution of tornado power (P) across the cumulative distribution of tornado days (i.e., days with 1 or more (E)F1+ tornadoes). Diagonal black line in **a** shows the line of equality on which P is hypothetically distributed equally across all days. **b** Annual Gini coefficients for P between 1954 and 2017. A local regression curve (loess) along with 95% confidence interval (CI) is shown in **b**. The trend statistic and significance values are provided in Table 1

also clearly seen in the distribution of casualty counts per tornado day magnitude (Fig. 6b). The average casualty counts on days with 1–9, 10–19, and 20+ (E)F1+ tornadoes are 4, 40, and 202, respectively, while the median casualty counts on the same days are 0, 11, and 55. Casualty counts tend to be greater on high-magnitude tornado days not only because of the large number of tornadoes but also because more power is dissipated on these days (Fig. 7). The Spearman's *rho* rank correlation between tornado day magnitude and daily accumulated tornado power is 0.67 ($p < 0.001$). The greater power dissipated on days with many tornadoes is related not only to the large number of tornadoes but also to larger percentages of stronger tornadoes (i.e., those rated (E)F2–(E)F5) (Moore 2017; Elsner et al. 2019) and longer-track tornadoes on average (Fig. 8). Like tornado day magnitude, daily accumulated tornado power is also related to casualty counts—the Spearman's *rho* rank correlation between daily accumulated tornado power and daily casualty count is 0.53 ($p < 0.001$).

Daily and per event casualty counts are sensitive to the geophysical attributes of tornadoes (e.g., tornado numbers, path length, path width, intensity, time of day), the socioeconomics and demographics of the affected population (e.g., income, age, disability, non-English speaking, pre-existing health conditions), and the built environment (e.g., age of structures, density of structures, number of manufactures and mobile homes) (Boruff et al. 2003; Merrell et al. 2005; Ashley et al. 2008; Sutter and Simmons 2010; Simmons and Sutter 2011; Dixon and Moore 2012; Ashley and Strader 2016; Strader et al. 2016, 2017; Fricker et al. 2017; Elsner et al. 2018; Fricker and Elsner 2019). Changes to any of these vulnerability factors will affect casualty counts. For example, per tornado casualty counts will likely increase as population and the built environment expand, even if tornado numbers and intensities are stable (Ashley et al. 2014; Rosencrants and Ashley 2015; Ashley and Strader 2016; Strader et al. 2016, 2017a and b; Strader and Ashley 2018; Strader et al. 2018). Likewise, per tornado casualty counts will likely increase as the power of tornadoes increases (Elsner et al. 2019) and per tornado day casualty counts will likely increase as days with many tornadoes become more common (Brooks et al. 2014; Elsner et al. 2015; Moore 2017; Moore and DeBoer 2019; herein), assuming that tornadoes continue to impact people and that the sturdiness of the built environment and the number of shelters remains unchanged. Fortunately, the numbers of casualties per year on days with 1–9 and 10–19 tornadoes have declined (Fig. 9). Improved detection and warnings coupled with sturdier structures and more shelters have likely contributed to these declines (Merrell et al. 2005; Simmons and Sutter 2005, 2008). The number of casualties per year on days with 20+ tornadoes shows marked interannual variability, but does not decrease over time as notably as the 1–9 and 10–19 series (Fig. 9).

The increased concentration of tornadoes may also have consequences for the climatology of tornadoes in the USA.

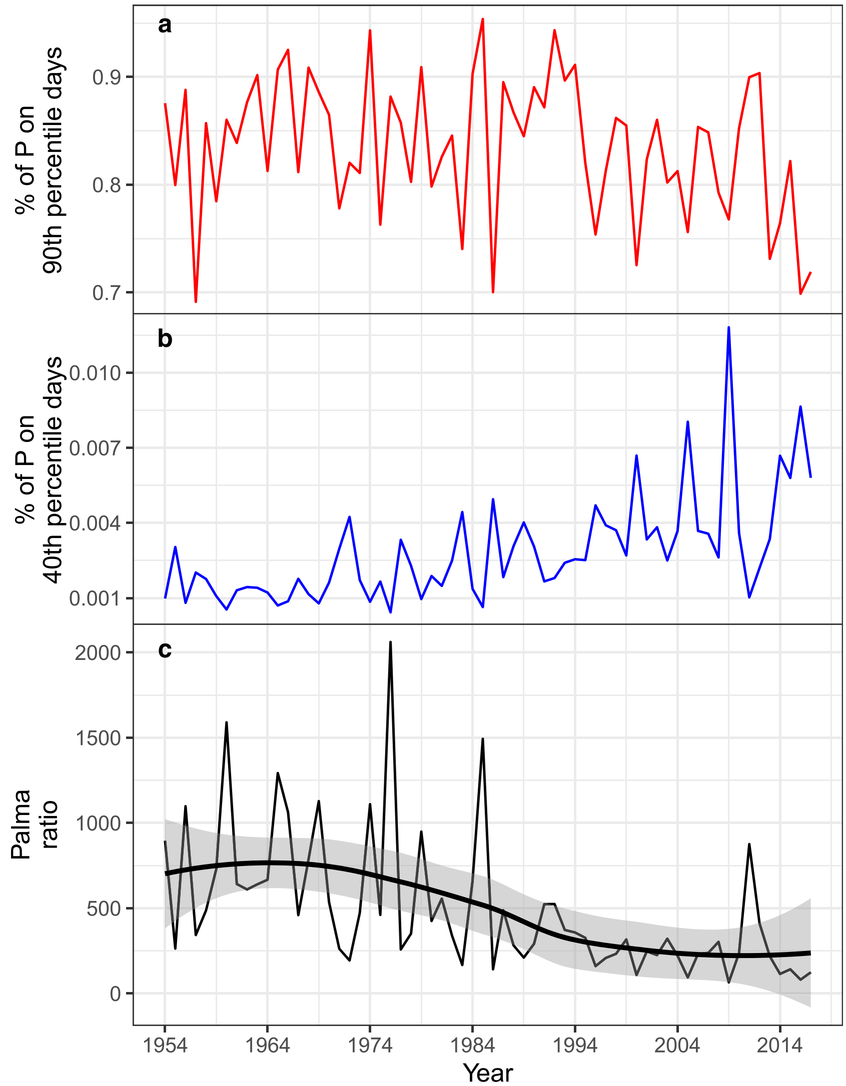

Fig. 5 **a** Annual percentages of tornado power (P) occurring on or above 90th percentile tornado days (i.e., those with the greatest P). **b** Annual percentages of P occurring on or below 40th percentile tornado days (i.e., those with the least P). The 90th percentile/40th percentile ratio, or the Palma ratio, is shown in **c**. A local regression curve (loess) and the 95% CI are shown in **c**. The trend statistic and significance value are provided in Table 1.

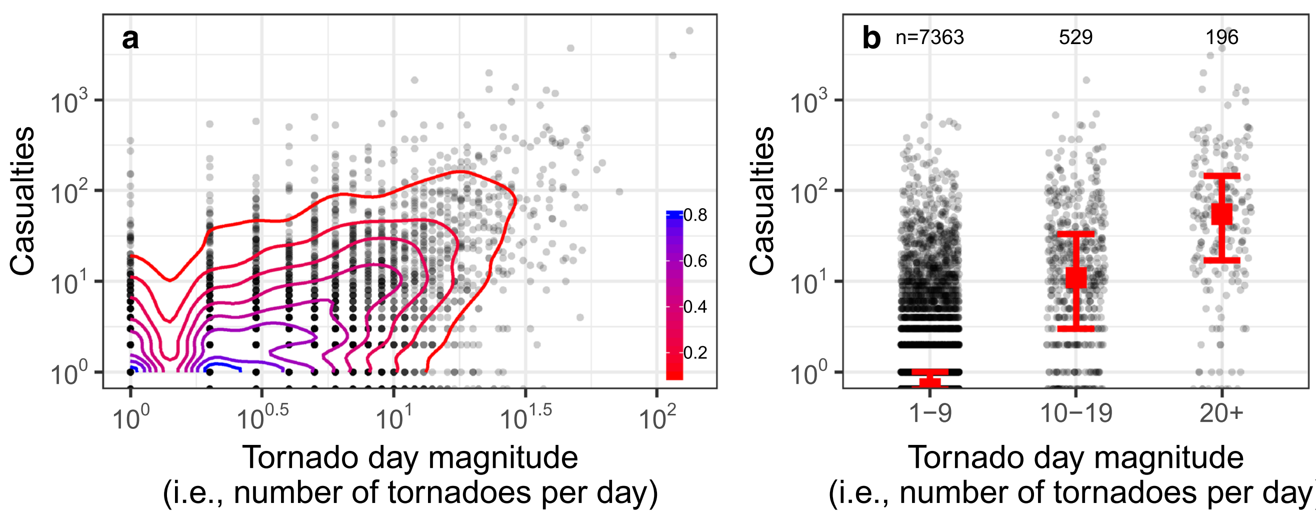

Fig. 6 **a** Daily casualty counts distributed across tornado day magnitude (i.e., the number of tornadoes on a given day). Contours represent the density of the points and illustrate the positive correlation between casualty count and tornado day magnitude. The distributions of casualty counts across the 1–9, 10–19, and 20+ tornado day magnitudes are shown in **b**. The red boxes in **b** show the median casualty counts and the error bars extend to the 25th and 75th percentiles.

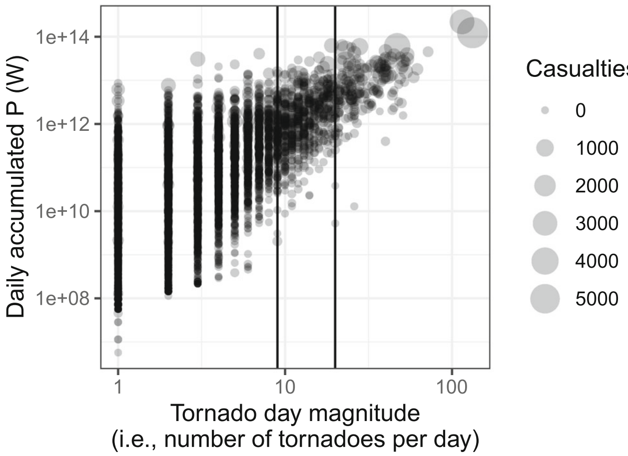

Fig. 7 Distribution of daily accumulated tornado power (P) across tornado day magnitude (i.e., the number of tornadoes on a given day). The size of the points is scaled by casualty count. The vertical lines are set at 9 tornadoes per day and 20 tornadoes per day.

Tornadoes that occur on days with many events tend to concentrate farther east than those that occur on days with fewer events (Fig. 10). Therefore, as the percentage of tornadoes occurring on days with many tornadoes increases, the spatial distribution and dispersion of tornadoes are likely to change. Evidence of such changes have recently been documented. Tornado counts have decreased over time in the Great Plains and increased over time in the Southeast and southern Midwest (Agee et al. 2016; Ashley and Strader 2016; Moore 2018; Gensini and Brooks 2018; Moore and DeBoer 2019), and the center of tornado activity has shifted slightly eastward (Boruff et al. 2003; Moore 2017; Moore and DeBoer 2019). The spatial dispersion of tornadoes has decreased over time, most notably in spring, summer, and fall (Moore and McGuire 2019). The shift toward the southeastern USA and decreased spatial dispersion, in turn, have implications for casualties because tornadoes in this region tend to produce more casualties than those in other regions, owing largely to high social vulnerability, abundance of manufactured and mobile homes, and reduced visibility (Boruff et al. 2003; Cutter et al. 2003; Ashley 2007; Schmidlin et al. 2009; Sutter and Simmons 2010; Elsner et al. 2018; Strader and Ashley 2018; Strader et al. 2019; Fricker and Elsner 2019).

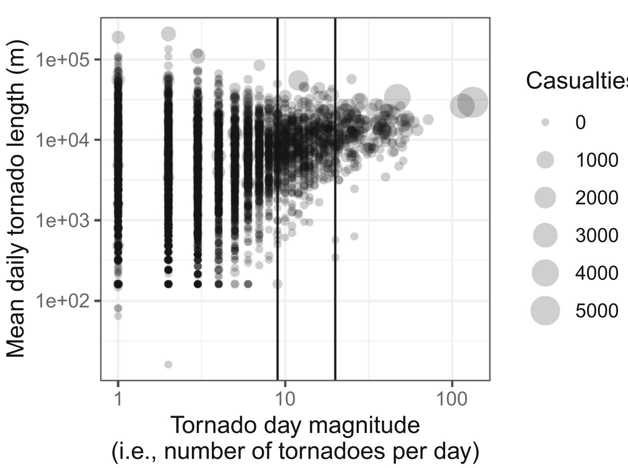

Fig. 8 Mean daily tornado path length distributed across tornado day magnitude (i.e., the number of tornadoes on a given day). The size of the points is scaled by casualty count. The vertical lines are set at 9 tornadoes per day and 20 tornadoes per day.

Annually accumulated tornado power is highly concentrated on relatively few days in a given year but is becoming less concentrated. This suggests that the annual increase in tornado power seen in Elsner et al. (2019) is, in part, likely due to an increasing baseline of weaker tornadoes than to an increasing baseline of stronger tornadoes. Despite the decrease, tornado power is still highly concentrated. Even in the last 20 years of the record, at the end of the observed declining trend, an average of 81% of the annually accumulated tornado power occurred on only the top 10% of tornado days (i.e., those with the greatest daily accumulated tornado power). With the low rate of decline, tornado power will likely remain highly concentrated.

4 Conclusion

The Gini coefficient, Palma ratio, and 20+/1–9 ratio were computed for each year between 1954 and 2017 to measure the annual concentration of tornadoes and tornado power in the USA. The Mann-Kendall trend test and Theil-Sen slope estimator were used to determine if tornadoes and tornado power became more concentrated or less concentrated over time. According to all measures, tornadoes in the USA have become more concentrated over time. The average Gini coefficient for all days, for example, increased 11% (0.79 to 0.88) between the early (1954–1973) and late (1998–2017) 20-year periods. The Palma and 20+/1–9 ratios averaged over the same 20-year periods increased by even larger percentages—63% (2.4 to 3.9) and 306% (0.16 to 0.65), respectively, showing that the greatest changes are occurring in the tails of the tornado day magnitude frequency distribution. These trends fall in line with the growing body of literature that provides evidence of increased concentration of tornadoes in the USA (e.g., Brooks et al. 2014; Fuhrmann et al. 2014; Elsner et al. 2015; Tippett and Cohen 2016; Tippett et al. 2015; Moore 2017, 2018; Moore and DeBoer 2019). Also, according to all measures, tornado power became less concentrated over time, particularly toward the end of the record. Despite these declining trends, the Gini coefficient and Palma ratio illustrate the high concentration of tornado power. Eighty percent or more of the power dissipated in most years occurred on just the top 10% of tornado days with the most power dissipation.

Historically, casualty counts have been greater on days with large numbers of tornadoes on which more power is dissipated. The median casualty count for days with 1–9 (E)F1+ tornadoes is 0 but increases to 11 on days when 10–

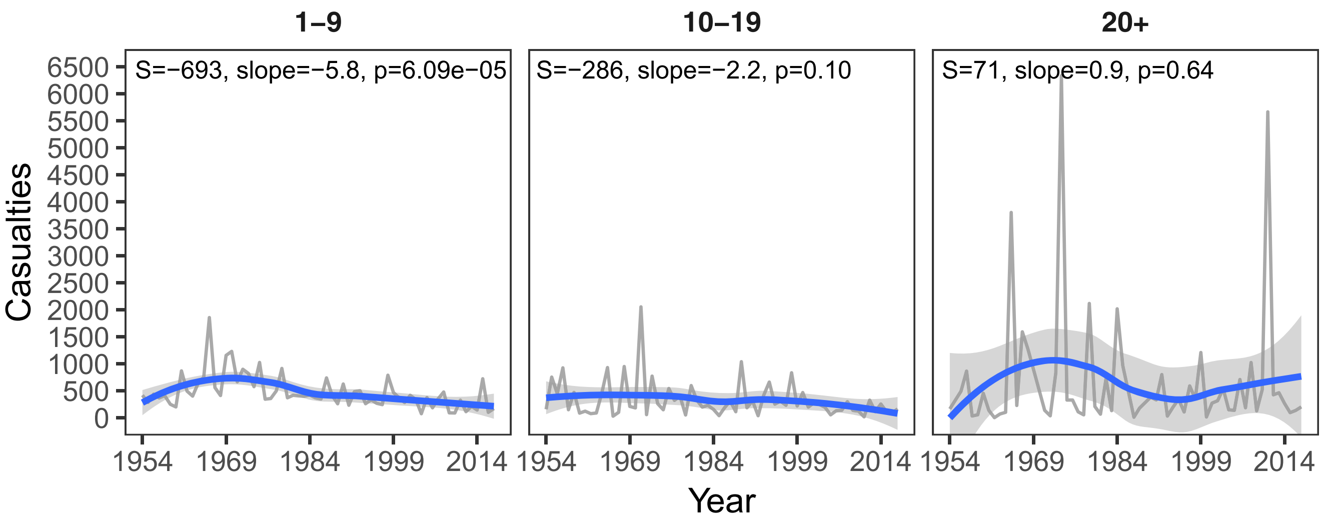

Fig. 9 Time series of annual casualty counts for the 1–9, 10–19, and 20+ tornado day magnitudes. Mann-Kendall test statistics (S), Theil-Sen slope estimates (slope), and significance levels (p) are shown in each panel.

19 (E)F1+ tornadoes occur and another 400% (to 55) when 20+ (E)F1+ tornadoes occur. The increased concentration of tornadoes (and especially the increasing frequency at which days with 20+ (E)F1+ tornadoes are occurring), therefore, has the potential to elevate casualty counts, all else being equal. The increasing frequency of tornadoes (and, again, especially the increasing frequency at which days with 20+ (E)F1+ tornadoes are occurring) in the southeastern USA also has the potential to elevate casualty counts because of the region's vulnerable population (Boruff et al. 2003; Cutter et al. 2003; Ashley 2007; Schmidlin et al. 2009; Sutter and Simmons 2010; Elsner et al. 2018; Strader and Ashley 2018; Strader et al. 2019; Fricker and Elsner 2019).

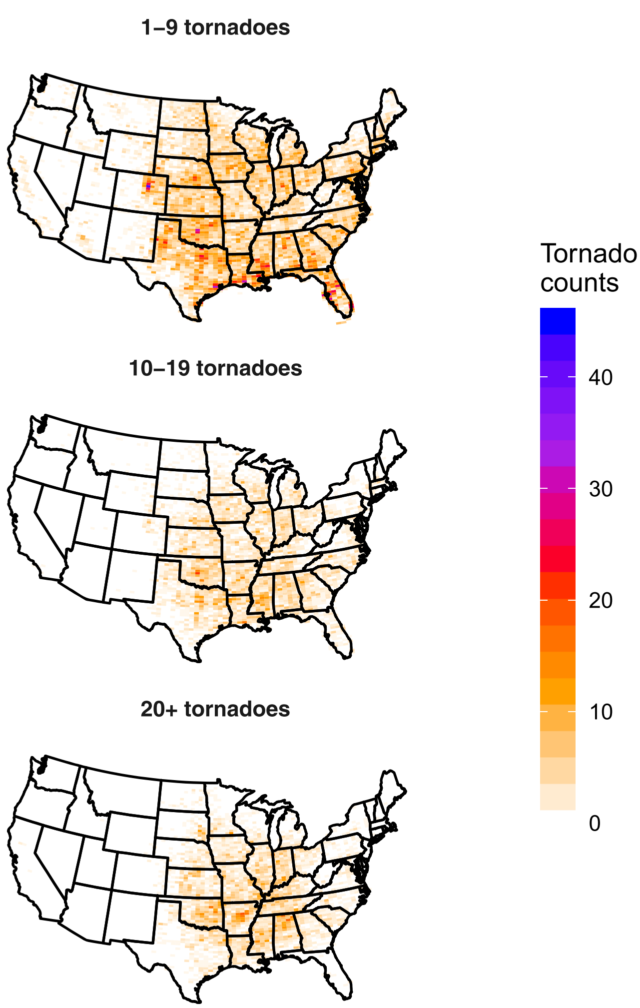

Fig. 10 Spatial distributions of (E)F1+ tornadoes on days with 1–9, 10–19, and 20+ tornadoes.

Mounting evidence shows that tornadoes are concentrating on fewer days. The next step in this line of research is climatological attribution of this trend. Attribution is beyond the scope of this study, but we suggest that future research test multiple hypotheses. Non-climatological factors like improved detection technology are known to increase the number of tornadoes in the USA (Verbout et al. 2006), but it is difficult to explain an increase in concentration with such factors. Improved tornado detection should heighten the probability of occurrence across the tornado day magnitude spectrum, not just the probability of occurrence of days with many tornadoes (Brooks et al. 2014). Nonetheless, future efforts should try to determine if changes in technology and reporting can explain portions of these trends. Alternatively, environmental changes might have led to these trends in tornado concentration. It has already been shown that storm relative helicity has increased over time along with the number of tornadoes per outbreaks (Tippett et al. 2016). The recurrence of tornado outbreaks with meridional jet stream patterns (Doswell III et al. 2012; Mercer et al. 2012; Schultz et al. 2014) introduces another possible environmental contribution—Arctic amplification (i.e., amplified warming in the Arctic and the reduced pole-to-equator temperature gradient) and increased waviness of the Northern Hemisphere polar jet stream (Cohen et al. 2014; Francis and Vavrus 2015; Mann et al. 2017). Additional research is needed to determine if tornado outbreak-favorable jet stream patterns have increased in frequency, thus increasing the likelihood of tornado outbreaks. Coupled with a better understanding of the way people behave during tornado events, how people perceive tornado threats, and improved shelter systems (e.g., Schmidlin et al. 2009; Sutter and Poitras 2010; Senkbeil et al. 2012; Chaney et al. 2013; Klockow et al. 2014; Ash 2017; Ellis et al. 2018; Strader et al. 2019), the insight gained from testing these and similar hypotheses will refine our understanding of tornado risk, help improve tornado outlooks, and potentially reduce casualties.

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