Historical Analysis of U.S. Tornado Fatalities (1808–2017): Population, Science, and Technology

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ABSTRACT

The record of tornado fatalities in the United States for over two centuries (1808–2017) and decadal census records have been examined to search for historical trends. Particular attention has been given to the response to population growth and expansion into the tornado-prone regions of the country. The region selected includes the Tornado Alley of the central Great Plains, the Dixie Alley in the southeastern states, and the adjoining states in the Midwest that collectively encompass a 21-state rectangular region. The data record has been divided into two subintervals, Era A (1808–1915) and Era B (1916–2017), each of which consists of three equal-length periods. Era A is characterized by a growing and westward expanding population along with a basic absence of scientific knowledge, technology, and communications (for prediction, detection, and warning). This is followed by a renaissance of discovery and advancement in Era B that contributes to saving lives. The aforementioned periods are defined by a set of notable events that help to define the respective periods. A death per population index (DPI) is used to evaluate the 21 states in each era; there is a rise of mean DPI values to a maximum of 1.50 at the end of Era A and a subsequent fall to 0.21 at the end of Era B. It is also shown for all three periods in Era B that the deadliest tornado states, in ranked order, are Arkansas, Mississippi, Alabama, and Oklahoma. Suggestions are presented for ways to continue the decreasing trend in DPI, which would imply that the death rate increase is not as fast as the rate of population increase (or would even imply a decreasing death rate).

1. Introduction

Consideration of spatial and temporal changes in U.S. tornado activity continues to capture the attention of the scientific community (e.g., Ashley 2007; Elsner et al. 2015; Agee et al. 2016) as well as in the context of possible climate change effects (see Widen et al. 2015). Brooks et al. (2014) have shown the increasing variability in tornado activity accompanied by a constant to slight decrease in annual tornado counts (also see Agee and Childs 2014). The current study has chosen to take a step back in time (1808–2017) to search for evidence of the effect of tornadoes on the emerging U.S. population growth and its westward expansion with a particular focus on tornado fatalities. The completeness of tornado records is often questioned and has evolved over time, especially since 1954 (see Verbout et al. 2006). It is worth noting that today's tornado archives are most likely capturing all strong and violent tornado events. Ashley (2007) comments that fatality data may be the most complete aspect of the historical tornado data record. His paper also discusses the factors that have historically affected the occurrence of tornado deaths. A study encompassing over two centuries of tornado events would be seemingly impossible; however, a new approach is presented that addresses and helps to define the most tornado-prone regions based on tornado deaths. It is documented that significant tornadoes, (E)F2–(E)F5 on the (enhanced) Fujita scale, are responsible for the large majority of tornado fatalities (see, e.g., Concannon et al. 2000). Even though the number and location of past tornado events are largely unknown, fatality records do exist. The starting premise is simple: namely, that tornado deaths require the presence of population and the occurrence of sufficiently strong tornadoes. Over time, there have been tornadoes where there were no people and also people where there were no tornadoes. However, it is assumed that the historical records of tornado deaths can give a

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useful measure for historically defining the regions where strong and violent tornadoes have occurred when population density is considered.

The objective of this research has been to develop a method that analyzes tornado deaths for a 21-state region (depicted in Fig. 1) to potentially show where the most deadly tornado states and regions have existed through time. These states have been selected to include both the Tornado Alley in the central Great Plains as well as the Dixie Alley in the southeastern states, along with adjoining states in the Midwest region. These 21 states represent a contiguous (nearly rectangular) geographical region contained between 80° and 105°W that extends from the Gulf Coast to the Canadian border. This analysis approach has also helped to define two eras that typify the relationships among tornado fatalities, population growth, and the emergence of scientific knowledge and technology in support of improved prediction and warning. *Era A* is defined by the period from 1808 to 1915 and is characterized by the virtual existence of little to no tornado understanding or warning as well as the growth and expansion of the population into tornado-prone regions. *Era B* is defined by the period from 1916 to 2017, which is characterized by a continuous increase in knowledge and technology for the improvement of all systems that can save lives in the face of a rapidly increasing population.

Fatalities associated with tornadoes involve not only people in the path of significant tornadoes but the type of response that individuals have when they are warned of (or see) an approaching event. A tornado risk assessment by Standohar-Alfano and van de Lindt (2015) has provided a probabilistic tornado hazard index for the United States (which can be extended to other geographical locations) that is based on an analysis of data records from 1974 to 2011. Boruff et al. (2003) have examined the frequency of tornado hazards for the period 1950–99 and have searched for geographical shifts in spatial frequency. A discussion of tornado forecasting, warning, and response, which have continually improved for nearly two decades, was provided by Golden and Adams (2000). There has also been an increased focus on vulnerability from a variety of societal exposures (e.g., Hall and Ashley 2008; Dixon and Moore 2012; Ashley and Strader 2016; Strader and Ashley 2018). Fricker et al. (2017) have also deployed dasymetric mapping to assess tornado casualties associated with population density along tornado tracks for the period of 1955–2016. Future work is expected to pursue in more detail the role of socioeconomic and societal factors, such as housing codes, mobile homes, increasing senior citizen population in tornado-prone regions, nocturnal tornadoes, community awareness, and social media. However, in considering a period of two centuries, there is no consideration in Era A of hazard assessment and risk analysis, no tornado forecast, warning, and response, and no supporting technology (thus, it is a century that is in total contrast to Era B).

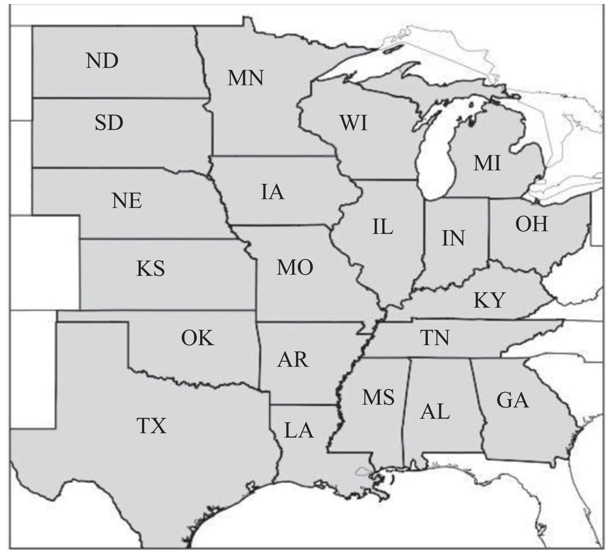

FIG. 1. The 21-state region of the United States that was selected for study.

The record of deaths has been divided into six time periods; the first three are in Era A, and the next three are in Era B. They are, respectively, period I: 1808–43, period II: 1844–79, period III: 1880–1915, period IV: 1916–49, period V: 1950–83, and period VI: 1984–2017. Criteria and discussion will follow that help to explain the choice of these six time periods, the records of tornado deaths, and the use of the U.S. Census population over time for calculating a normalized death per population index (DPI) for each state. Results will be presented to show that there are four contiguous states that rank above the 80th percentile of DPI values for each of the Era B time periods, identifying them as the most deadly tornado states (a feature that has been consistent for over a century in a region that combines the hearts of both the traditional central Great Plains Tornado Alley and the Dixie Alley). These states (in ranked order) are Arkansas, Mississippi, Alabama, and Oklahoma, which are located just south of the centroid of tornado activity calculated by Boruff et al. (2003). Their decadal centroid is shown to drift southeast over time, approaching the northeastern corner of Arkansas during the last decade of the twentieth century.

2. Historical background

There were several potential key event dates and times for defining the six time periods of this study, but the authors have chosen 1880 as one of the more critical events [which is consistent with Ashley (2007)]. This is based in part on the many well-known professional papers on tornadoes by J. P. Finley (see, e.g., Finley 1884) as well as key historical tornado data presented by Grazulis (1993). The legacy of Finley has been documented in a review paper by Galway (1985). The next critical date selected was 1916, when the U.S. Weather Bureau became the official national collection agency for tornado reports (Bradford 1999). These two key dates, along with the start of the modern tornado data record in 1950, define period III (1880–1915) and period IV (1916–49). It is noted that these have lengths of 36 and 34 years, respectively, and are also the respective ending and beginning of Era A and Era B (each with three equal time periods). Many notable events are listed in Table 1, but it was desirable for all three periods in each respective era to have the same length (and they are defined accordingly). A review of several key historic events has been provided by Galway (1985). Similarly, a review of critical dates and events has also been provided by Bradford (1999), many of which are listed in Table 1. In general, these notable events focus on the beginning and evolution of forecasting principles, detection, and reporting methods along with the development of key technology such as radar, computers, and satellites (and continuously improved instrumentation systems for measurement and computational analysis).

a. *Era A (1808–1915)*

This period of time marks the beginning of U.S. population growth and westward expansion from the East Coast to the central Great Plains. Prior to this era the first recorded tornado death was that of a Native American in Massachusetts in 1680 (see Grazulis 1993). The first recorded tornado fatality for the 21-state region in this study was in 1804 in Georgia (and there are only a few deaths at the start of period I in 1808). It is also noted that ''zero deaths'' are to be interpreted as ''no-data zero deaths''; there were likely Spanish, Mexican, and Native American deaths in the earlier Era A territorial time periods. Even if there were such records of deaths, the DPI could not be calculated because the total population was not known. The DPI concept presented in the next section is designed to accommodate a small (state or territory) population resulting in only a few tornado deaths even though tornadoes were occurring. In general, it can be noted that Era A is characterized by little to no scientific knowledge of tornadoes and virtually no technology or communications capability to warn the population, with the only exception being the early observational studies by Finley toward the end of the era. The most noteworthy tornado safety practice that evolved during Era A was the use of root cellars (a place for storing potatoes, carrots, radishes, and so on; also see Bradford 1999), which became the earliest version of the earth dome cyclone cellars. Conceptually, the DPI value is expected to rise through Era A and then reverse in Era B (which is characterized by scientific and technological advancement; see Table 1).

1) PERIOD I (1808–43) AND PERIOD II (1844–79)

As noted above, the start and end dates of these periods have been defined (see Table 1) and can be analyzed from the viewpoint of the westward expansion of the population and the record of tornado fatalities. The U.S. Census population data record began in 1790 and thus provides a reliable statistic for these two periods (as well as all subsequent periods, with caveats previously noted). Tornado fatalities during these two periods, taken from Grazulis (1993), came largely from newspapers, newsletters, and journal accounts. However, the first chief meteorologist (Cleveland Abbe) was appointed in 1869 and was subsequently named director of the new weather service that was established in 1870 within the Signal Service. Accordingly, any inference about the frequency and strength of tornadoes at that time was largely unknown, so any potential result that shows a low DPI value could be due to only a few tornadoes (as long as there were a sufficient number of people located in the region). At the beginning of period I there were only four states and multiple territories, whereas by the end of period II this had increased to 18 states along with the Dakota and Oklahoma territories. Similarly, the population for the 21-state region was only 1 329 722 in 1810 but subsequently had increased to 20 599 630 by 1870 (reflecting a population growth rate averaging around 321 165 per year). This population increase may partially explain an apparent trend in killer tornadoes reported by Brooks and Doswell (2002), but that statistic is not the same as counting tornado fatalities. It is also noted that an increasing DPI represents a death rate that is increasing faster than the population rate of increase.

2) PERIOD III (1880–1915)

As a result of the efforts by Finley, the third period brought into existence the concept of meteorologists keeping tornado records, the effort to seek out volunteers, and the effort to establish a reporting network. Finley's work led to the first publication on the climatology of 600 U.S. tornadoes (see Table 1). Also, the original weather service moved to the U.S. Department of Agriculture and was formally named the U.S. Weather Bureau in 1890, opening the door for increased attention to obtaining and documenting tornado events and fatalities (although the inherited ban on the use of

TABLE 1. The six time periods selected for this study as well as some of the notable events, including developments and improvements in weather prediction and technology.

Time period	Some notable events
I (1808–43)	1808—The year selected to establish three consecutive 36-yr periods, as based on the defined critical notable events that established periods III and IV
II (1844–79)	1844—The year selected to establish three consecutive 36-yr periods
	1869—Cleveland Abbe was appointed as chief meteorologist in the Signal Service
	1870—The weather service was established in the Department of War
	1877—John Finley enlisted in the Signal Service (Galway 1985)
III (1880–1915)	1880—The beginning of Finley's detailed tornado records
	1884—Finley's climatology of 600 tornado reports (1794–1881)
	1884—First experimental tornado prediction by Finley
	1885—The chief Signal Service officer banned the use of the word "tornado"
	1890—The U.S. Weather Bureau was established in the Department of Agriculture
IV (1916–49)	1916—The Weather Bureau became the official collection agency for tornado reports
	1919—The American Meteorological Society was formed
	1938—The ban on the use of "tornado" in weather products was removed by the Weather Bureau
	1940—The Weather Bureau moved to the Department of Commerce
	1945—The electronic computer ENIAC was created, leading to the first experimental weather prediction in 1950
	1948—Operational tornado forecast by Fawbush and Miller (see Maddox and Crisp 1999)
V (1950–83)	1950—The start of the modern tornado record
	1950—The Weather Bureau lifted the ban on issuing tornado warnings to the public
	1952—The SELS unit was established; first public tornado forecast
	1953—First detected radar hook echo by the Illinois State Water Survey in Champaign
	1957—Creation of the Weather Service Radar (WSR57; used by the National Severe Storms Project in 1962)
	1960—*TIROS-1* was the first weather satellite (polar orbiting)
	1964—NSSL was established in Norman
	1966—SELS became NSSFC
	1970—The U.S. Weather Bureau was renamed as the National Weather Service
	1971—The Fujita tornado intensity scale was introduced (Edwards et al. 2013)
	1975—The Geosynchronous Orbiting Earth Satellite (*GOES-1*) was launched into orbit
	1982—The Weather Channel debuted
VI (1984–2017)	1984—The year selected to establish three consecutive 34-yr periods
	1988—NEXRAD Doppler radar (WSR-88D) was created; implemented in the 1990s
	1995—NSSFC was renamed SPC
	1997—SPC moved from Kansas City to Norman
	1999—NSSL discovered a tornado debris signature with experimental dual-polarization radar
	2007—The Fujita scale was replaced by enhanced Fujita scale (see Edwards et al. 2013)
	2011—First operational radar by NWS that utilizes dual-polarization technology
	2015—Continuously improving contribution by social media to warning
	2016—*GOES-R* launched; it became operational *GOES-16*

the word "tornado" in weather information hindered public safety; also see Bradford 1999).

b. Era B (1916–2017)

As indicated in previous discussion, Era B represents a renaissance of progress, discovery, and improvements in communications and technology relating to tornado prediction, observation, warning, and public safety, along with the establishment of building codes. The population was increasing rapidly in the 21-state tornado-prone region yet the trend of an increasing DPI was subject to being reversed by the onset of the aforementioned advancements.

1) PERIOD IV (1916–49)

In 1916 the U.S. Weather Bureau became the official collection agency for tornado reports, an event that also represents the start of period IV (Bradford 1999). This was followed shortly by the establishment of the American Meteorological Society in 1919. In 1938 the Weather Bureau lifted the ban on use of "tornado." The bureau moved to the U.S. Department of Commerce in 1940. Positive spinoffs from World War II included the advent of radar as well as the subsequent development of the electronic computer, both representing technological advancements to assist future tornado prediction and warning. Also, this period experienced what many still call today "the best tornado forecast ever made" namely, the Fawbush and Miller prediction for Tinker Air Force Base in 1948 (see Maddox and Crisp 1999).

2) Period V (1950–83)

This period begins with the start of the modern tornado record, as well as the Weather Bureau lifting the ban on issuing tornado warnings to the public. Period V represents a period of substantial effort to study, observe, and predict tornadoes, pushing the envelope of scientific knowledge. This includes the introduction of the NOAA Weather Radio along with the "SKYWARN" Spotter program. This period also produced the Severe Local Storms (SELS) unit, the National Severe Storms Laboratory (NSSL), and the National Severe Storms Forecast Center (NSSFC), as well as the work by Ted Fujita that led to the introduction of a tornado intensity scale. For a complete review of tornado intensity estimation through time, see Edwards et al. (2013). Also, radar and satellites came into existence, allowing for identification of storms with hook echoes as well as the first weather observations from the polar-orbiting *TIROS-1* in 1960. The first radar hook echo was observed at Champaign, Illinois, on 9 April 1953 [see the report by Huff et al. (1954)]. Satellite technology and observations continued to improve with time, which ultimately led to the geosynchronous weather satellite (and the launch of *GOES-1* in 1975). The introduction of the Weather Channel in 1982 is another historical event that paved the way for communicating real-time severe weather and tornado information to the general population.

3) Period VI (1984–2017)

As is evident in Table 1, scientific and technological progress continued, highlighted by the introduction of Doppler radar, allowing for the detection of rotational velocity in storms that can be used to identify mesoscale vortices and the potential development of tornadoes. NSSFC was renamed the Storm Prediction Center (SPC) and subsequently moved from Kansas City, Missouri, to Norman, Oklahoma. This collocation of the NSSL, the SPC, and the University of Oklahoma enhanced the collaboration of expertise in severe storm research and prediction. This period also saw the emergence of storm chasing and field programs such as Project Vortex that included portable Doppler radar. Both radar and satellite technology also continued to advance with the dual-polarization Doppler (and the detection of the tornado debris signature), as well as the extremely high resolution imagery of the latest GOES satellite series.

3. Method

As discussed above, the approach in this study has been to examine *tornado fatalities* and *population density* per state (over a period of two centuries) in search of regions with the greatest frequency of suspected strong to violent tornadoes. Accordingly, an index was created that took into account these two variables. Population data came from the U.S. Census Bureau (https://www.census.gov/history/www/through_the_decades/overview/) collected on a 10-yr basis (from 1790 to 2010), including an estimate for 2017. Population averages were taken (using linear interpolation for growth) between two successive census decades to find the most representative value for the starting year (such as 1916). There were four values resulting from this method that were averaged to obtain the representative value for the entire period. Population values past 2010 were taken from estimates provided by the U.S. Census Bureau. It was also decided to compare statistics for individual states in the 21-state region. To allow for unbiased comparison of varying sizes of states, the average population was normalized by the unit area (km^2) of land per state (land area data were also retrieved from the U.S. Census Bureau).

The number of fatalities by state is available from the NOAA Storm Events Database (https://www.ncdc.noaa.gov/stormevents/) beginning with the year 1950, thus providing data for the final two periods in the current study. Prior to 1950, this study relies on documentation from Grazulis (1993) to compile a list of deaths dating back to 1808. The fatalities for a state were totaled within each time period and normalized by the state's land area, and similarly for the normalized average population for the given time period for each state. As seen in Eq. (1), the DPI incorporates the normalized tornado fatalities and population into a ratio for a *single state* within a time period, and Eq. (2) shows the DPI best defined in a much simpler form (because the land area of each state cancels out):

$$\mathrm{DPI} = \frac{\text{Total Deaths for the Period/Land Area of State}}{\text{Average Population for the Period/Land Area of State}} \qquad (1)$$

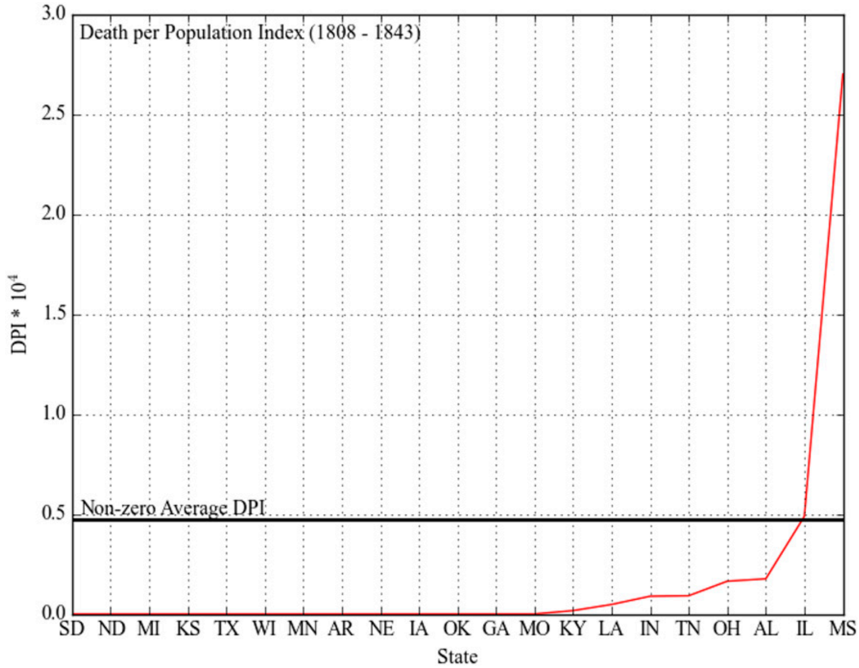

FIG. 2. Average DPI per state for period I (1808–43) scaled by 10^4. The mean DPI for 8 of the 21 states (excluding the 13 zero-value states) is 0.47, with 2 states above the average for tornado fatalities.

or

$$\text{DPI} = (\text{Total Deaths for the Period})_{\text{State}}/(\text{Average Population for the Period})_{\text{State}}. \quad (2)$$

As noted earlier, an increasing DPI value implies that the tornado death rate is increasing at a faster rate than the population growth (and a decreasing DPI implies that, even with a population growth rate, the tornado death rate is not as fast, or is even decreasing). The DPI values were calculated using Eq. (2) for each of the 21 states in the region of interest and are presented in the results discussed in the next section. The appendix, however, contains tables that provide, respectively, total deaths by state for each of the six periods, the average population for each state for each period, the scaled numerator value in Eq. (1), and the scaled denominator value in Eq. (1) (see Tables A1–A4). These tables are deemed a useful resource and are offered as a convenient reference.

An average DPI value was calculated for each of the six time periods (discussed in the next section). It is also possible to identify the deadliest tornado states, particularly in Era B, based on those states that are consistently above the average DPI throughout all three time periods. Average DPI values for both Era A and Era B were determined to search for any pattern of change for these time periods to analyze trends of tornado fatalities with respect to population growth and its westward migration (accompanied by the impact of scientific and technological advancement).

4. Results and conclusions

Era A has been defined as a time of small yet westward-migrating population with little to no scientific knowledge of tornadoes and virtually no technology or communications capability to warn the public. Figures 2–4 show the average DPI $\times 10^4$ for each state in periods I, II, and III. In Fig. 2 only two states (Mississippi and Illinois) were above the nonzero DPI average, which is likely due to having few people in most states and a lack of any complete tornado fatality record. In recognition of Native Americans living in the zero states, it is noted that many lives were likely lost at that time but not recorded. Figure 3 shows the effect of an increasing population, with 18 of the 21 states showing tornado deaths (no recorded fatalities yet in the Oklahoma and Dakota territories). In Fig. 4 for period III all 21 states are listed with tornado fatalities, and it is noteworthy that Oklahoma, Mississippi, and Arkansas had the highest DPI values. It appears that Oklahoma was influenced by the land rush in 1889, leading to a growing (and unprotected) and expanding population into a tornado-prone region. For all three successive time periods in Era A, the respective average DPI

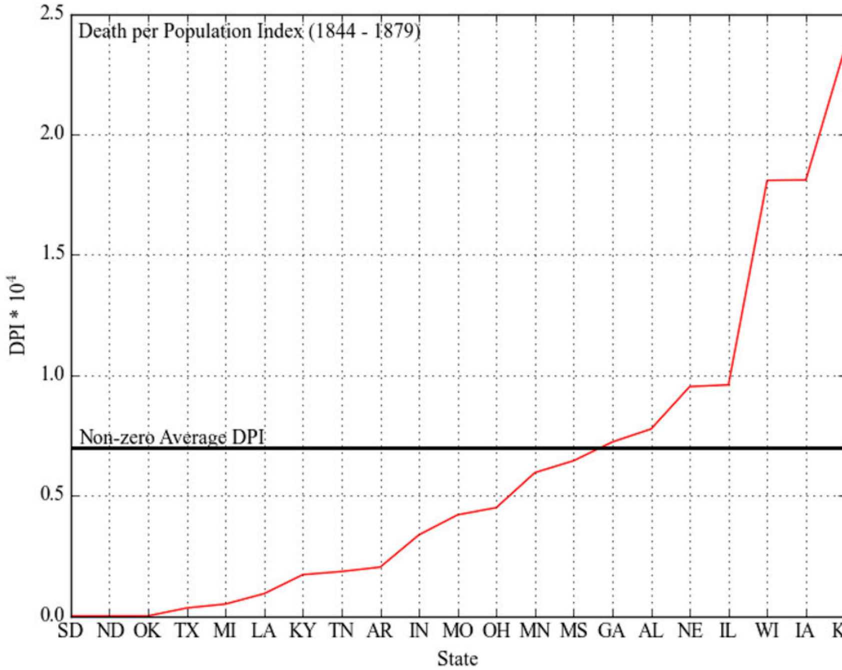

FIG. 3. Average DPI per state for period II (1844–79) scaled by 10^4. The mean DPI for 18 of the 21 states (excluding the three zero-value states) is 0.70, with 7 states above the average for tornado fatalities.

values are 0.47, 0.70, and 1.50, all of which reflect an increasing ''risk'' of tornado fatalities with time and population growth. As implied in earlier discussion, it is assumed that the tornado death risk has always existed.

Era B is characterized by rapidly increasing population in the 21-state region, which at first thought might imply more fatalities and an increasing DPI. However, key scientific understanding and relevant

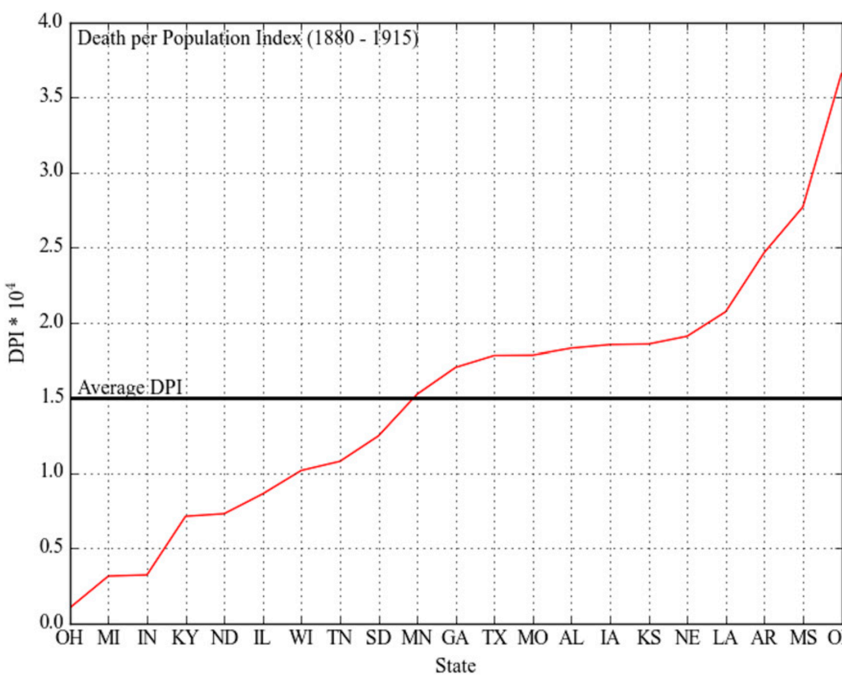

FIG. 4. Average DPI per state for period III (1880–1915) scaled by 10^4. The mean DPI for all 21 states is 1.50, with a total of 12 states above the average for tornado fatalities.

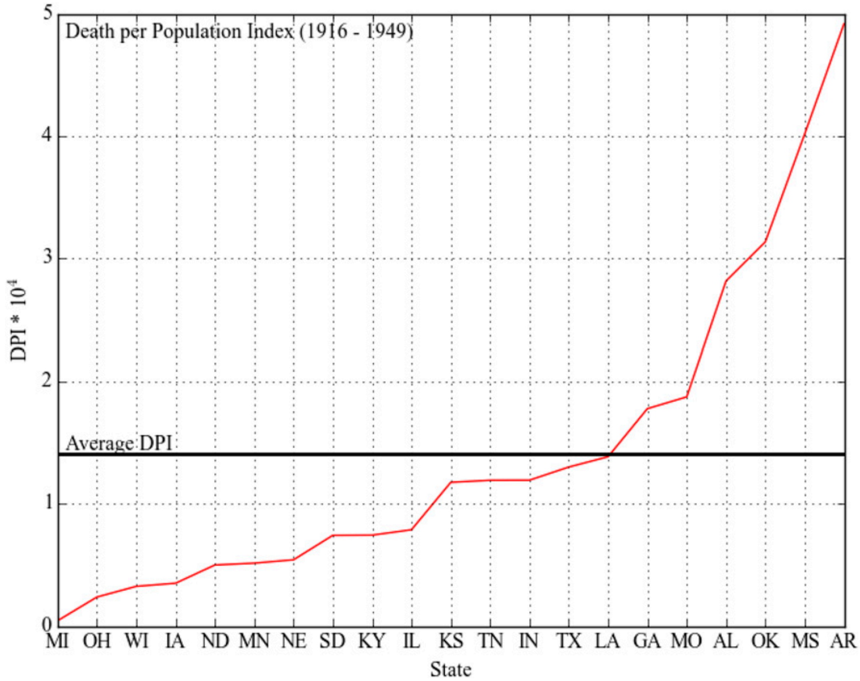

FIG. 5. Average DPI per state for period IV (1916–49) scaled by 10^4. The mean DPI for all 21 states is 1.41, with a total of 6 states above the average for tornado fatalities.

technology were also advancing rapidly, resulting in a steadily decreasing DPI value for all three time periods in Era B. Figures 5–7 show the plots of DPI for each state, with an average value of 1.41, 0.45, and 0.21 for periods IV, V, and VI, respectively. Figure 8 shows the states with the most-frequent above-average normalized tornado deaths, which identifies the four states that always ranked in the top five for each of the three periods

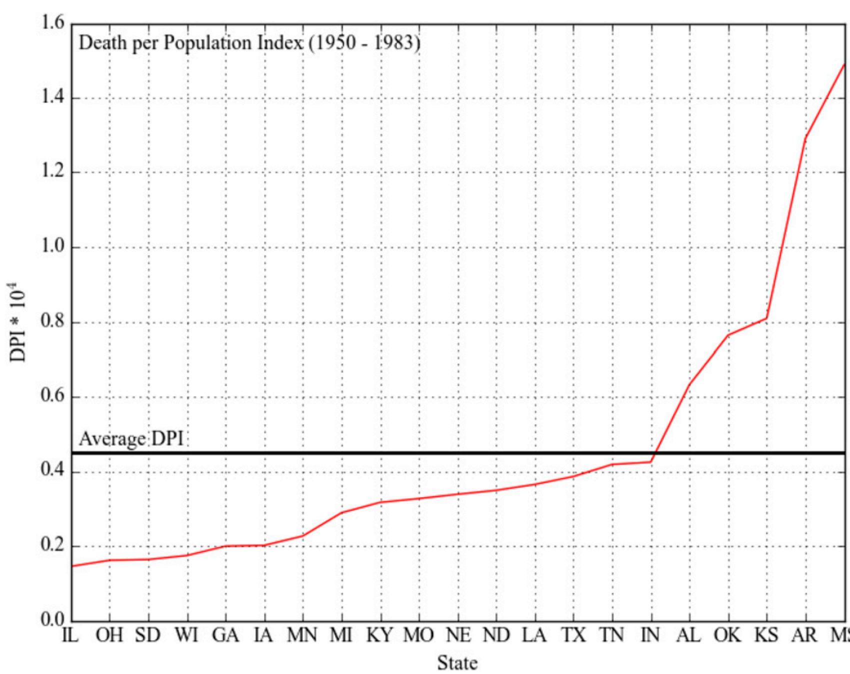

FIG. 6. Average DPI per state for period V (1950–83) scaled by 10^4. The mean DPI for all 21 states is 0.45, with a total of 5 states above the average for tornado fatalities.

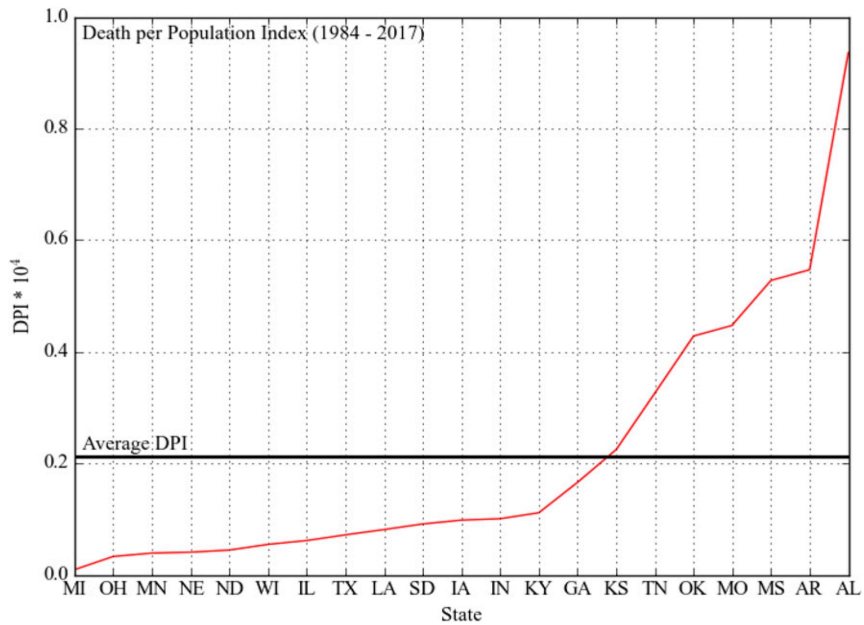

FIG. 7. Average DPI per state for period VI (1984–2017) scaled by 10^4. The mean DPI for all 21 states is 0.21, with a total of 7 states above the average for tornado fatalities.

in the 102-yr-long Era B. These states ranked in order of highest DPI value are Arkansas (first), Mississippi (second), Alabama (third), and Oklahoma (fourth). Other adjoining states that qualified for two of the three periods were Kansas and Missouri, and for one period it was Tennessee and Georgia.

The final result in this study is presented in Fig. 9, which shows an exponential function fit to each set of DPI values for Era A and Era B. Era A (1808–1915) is characterized by a rapidly rising trend in tornado fatalities resulting from increasing population and the westward expansion of settlers moving into tornado-prone regions. This is coupled with little to nothing in place to prevent fatalities. Without scientific and technological progress and improved safety practices, it is conceivable that Era A could have continued with even larger DPI values with thousands of deaths. Era B (1916–2017), however, reversed the trend and brought the highest DPI value of 1.50 (in period III) down to 1.41 (in period IV), 0.45 (in period V), and 0.21 (in period VI). All of the scientific and technological progress in Era B has saved thousands of lives. An asymptotic value of near zero deaths in Fig. 9 is unlikely, but a more reasonable question is how much lower the DPI value can go below 0.21 (if at all).

a. Suggestions for further decrease in DPI

Consideration should be given to an increased role of social media, a denser Doppler radar network, and an increased number of competent scientists and facilities for analysis and prediction, along with improved safety measures and warning practices by the general public. Wind-engineering research can continue to help with designing safe rooms for homes, offices, businesses, and schools. Local governments can implement legislature to require safe rooms in the more tornado-prone

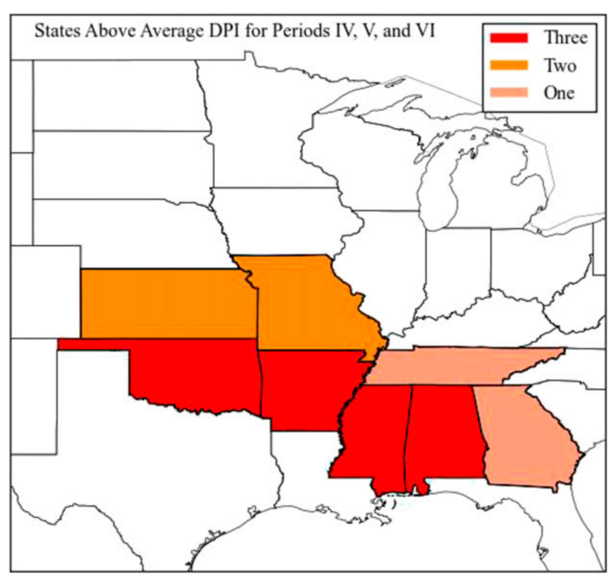

FIG. 8. Identification of states with the highest frequency of tornado deaths as based on DPI values. The occurrence of above-average DPI in any one (or more) of the periods is noted by the color code (not necessarily in chronological order). The four states in red always (1916–2017) ranked highest in tornado deaths during Era B.

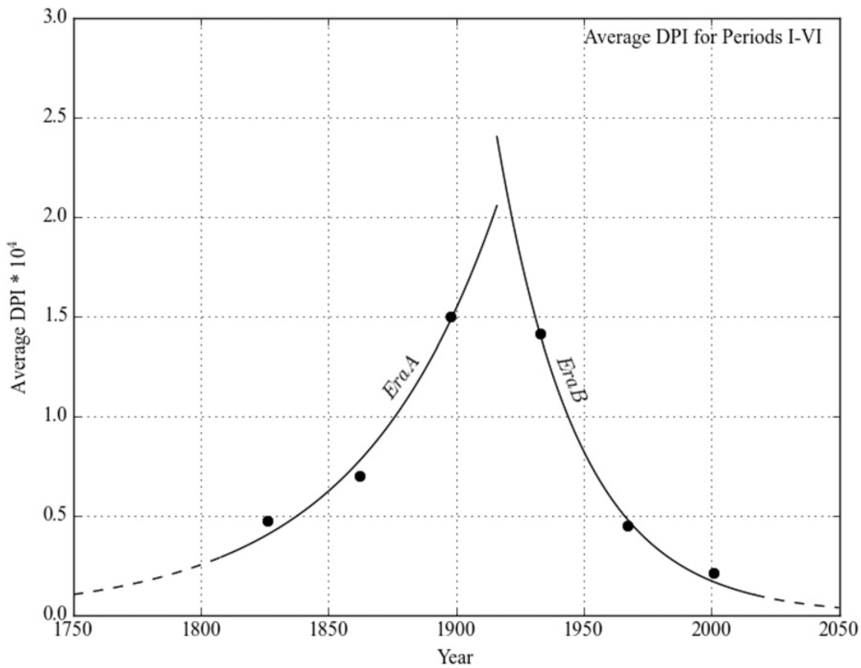

FIG. 9. Average DPI for three successive 36-yr intervals (Era A) represented by periods I, II, and III and three successive 34-yr intervals (Era B) represented by periods IV, V, and VI, plotted as time-centered points. The exponential decline in Era B (projected to be 0.05 by 2040) depicts that, even with a population growth rate, the tornado death rate is not as fast, or is even decreasing relative to population growth (provided that there are continued improvements in prediction, detection and warning, safety practices, and associated technological enhancements).

regions. Businesses should have tornado safety plans and also identify shelter locations that can be used when warnings are issued (as seen in schools and university facilities). The Tippecanoe School Corporation in Indiana had two schools that were severely damaged on Sunday afternoon 17 November 2013, and video from the schools showed debris fields that would have been harmful to students typically located there in safety drills. Plans for safety in the new school buildings were changed on the basis of this event. Safety offered by the bank vault in the Moore, Oklahoma, tornado on 20 May 2013 is another example, as well as the safe rooms added in schools rebuilt in Moore. Total community effort can save lives, and Federal Emergency Management Agency safe rooms could be added for minimal cost in businesses (even in shopping malls and large box stores). Homes without basements should include an interior reinforced safe room (and this could be enforced in new construction permits). Mobile homes are a high risk and these community parks should have storm shelters (preferably required by local government and housing authorities). Strader and Ashley (2018) have studied the regions of greatest vulnerability for tornado fatality risk for mobile homes, doing a comparison of the central and southeastern United States (which was extended down to a county-size scale for Kansas and Alabama). This finescale assessment offers useful information to community leaders and planners in preparing and executing best safety practices. Strader et al. (2017) have investigated the interaction of risk and vulnerability and how future changes may influence tornado disaster probability during the twenty-first century.

Perhaps the asymptotic value for the DPI decrease has been reached, and, as noted by Brooks and Doswell (2002) and discussed by Ashley (2007), data are supportive of a leveling off of deaths. That statistic alone would further lower the DPI value with continued population growth. It is noteworthy that the four identified states (Arkansas, Mississippi, Alabama, and Oklahoma) have persisted as the highest risk states for tornado deaths through the past 102 years (1916–2017) and through each of the three successive 34-yr periods. It is highly certain that population density will increase, with an increasing risk of catastrophic tornado death events associated with increasing urbanization and the increasing risk of fatalities in mobile homes (see Hall and Ashley 2008; Ashley and Strader 2016; Strader and Ashley 2018). Also of concern are sports and recreational events, as well as the added risk of concentrated cluster outbreaks of tornadoes in highly populated

TABLE A1. Total tornado deaths per state for each of the six periods.

State	Period I	Period II	Period III	**Era A total**	Period IV	Period V	Period VI	**Era B total**
AL	5	71	333	409	734	216	414	1364
AR	0	8	326	334	897	255	145	1297
GA	0	77	378	455	531	87	135	753
IA	0	131	388	519	86	56	29	171
IL	11	165	410	586	574	150	75	799
IN	3	45	79	127	385	205	61	651
KS	0	57	277	334	213	176	60	449
KY	1	20	148	169	195	102	45	342
LA	1	6	286	293	292	126	36	454
MI	0	4	78	82	20	234	9	263
MN	0	15	256	271	132	81	19	232
MO	0	51	529	580	626	146	249	1021
MS	50	48	422	520	800	338	147	1285
ND	0	0	26	26	32	22	3	57
NE	0	9	200	209	71	49	7	127
OH	14	105	43	162	152	158	37	347
OK	0	0	340	340	681	193	149	1,023
SD	0	0	53	53	48	11	7	66
TN	5	21	213	239	316	161	185	662
TX	0	2	548	550	738	413	153	1304
WI	0	127	205	332	94	72	29	195
Total	90	962	5538	6590	7617	3251	1994	12 862

regions. Edwards and Lemon (2002) reported a number of large event venues that had a near encounter with significant tornadoes. Nothing could compare to the size of a venue like the Indianapolis Motor Speedway on Memorial Day race day with 400 000 patrons in attendance (planning for repositioning to designated safe areas is a challenge, even with precise advanced warning). The reality is that some things can be eliminated (e.g., polio deaths); however, all tornado fatalities cannot be eliminated (but nonetheless the effort can be continued to minimize the number of deaths and conceivably sustain or lower the value of DPI even in the reality of a growing population).

It is important to note that this study has used total population figures and did not consider the possible effects of spatial patterns of hazard mortality rates. Population characteristics can be different from one region to another, and consideration should be given to such factors as age-adjusted differences and standardized mortality ratios. The study by Borden and Cutter (2008) provides insight on the need to consider such factors and not base everything on total population. Regional analyses of tornado death rates per million people per year for a portion of Era B (1985–2014) presented by Ashley and Strader (2016) suggest a stall in the declining tornado death rate. They also suggest that this stall may be caused by sociodemographic changes. It is further noted, however, that hazard mortality data did not exist in Era A and have only evolved in time through Era B, resulting in this study being based on total population data, with no ability to examine regional differences between the two periods.

b. *The value of the DPI*

Government agencies and businesses, along with community leaders and city planners, should be cognizant of how population growth and urban sprawl (among other things) enhance the tornado disaster risk (as documented and supported by the numerous citations in this paper). Not discussed here, and somewhat an unknown, is the effect of climate change and global warming on future risk of tornado disasters. Just as there are building codes established by engineers, including the U.S. Army Corps of Engineers, consideration should be given to the future determination of regional DPI tables and implications of such for population growth and expansion in tornado-prone regions.

Something similar to the finescale assessment reported by Strader and Ashley (2018) could be done for the DPI in the more tornado-prone regions. A range of values could be determined from the highest DPI to the lowest DPI, and local governments could use these values for planning and safety. These values could serve the interests of wind engineers, businesses, and insurance companies (including site selection and establishment of premiums, as done for other natural hazard risks such as floods and earthquakes). Fatalities are a result of human interaction and response to the natural hazard. This response can occur on three different time scales: 1) long-term preparation, 2) the day of the tornado threat,

TABLE A2. Total average population per state for each of the six periods.

State	Period I	Period II	Period III	Era A total	Period IV	Period V	Period VI	Era B total
AL	284 733	914 862	1 821 383	3 020 978	2 606 607	3 417 041	4 421 589	10 445 237
AR	49 649	394 967	1 322 897	1 767 513	1 824 074	1 975 574	2 653 208	6 452 856
GA	467 009	1 066 092	2 220 453	3 753 554	2 989 530	4 363 394	8 137 717	15 490 641
IA	27 844	723 753	2 095 810	2 847 407	2 459 028	2 780 260	2 954 487	8 193 775
IL	225 617	1 720 085	4 767 017	6 712 719	7 297 140	10 339 538	12 194 063	29 830 741
IN	339 224	1 337 891	2 466 022	4 143 137	3 230 782	4 828 417	6 061 275	14 120 474
KS	0	242 413	1 493 057	1 735 470	1 813 565	2 176 268	2 670 335	6 660 168
KY	608 051	1 168 340	2 082 094	3 858 485	2 625 075	3 221 078	4 041 053	9 887 206
LA	211 399	649 714	1 381 457	2 242 570	2 110 669	3 454 295	4 434 700	9 999 664
MI	90 638	813 857	2 494 430	3 398 925	4 595 607	8 100 771	9 683 401	22 379 779
MN	608	252 048	1 680 334	1 932 990	2 569 683	3 575 767	4 876 248	11 021 698
MO	190 310	1 215 348	2 966 351	4 372 009	3 343 335	4 467 850	5 564 562	13 375 747
MS	185 218	744 844	1 524 773	2 454 835	1 991 823	2 271 478	2 787 562	7 050 863
ND	0	5215	357 269	362 484	641 545	630 440	675 562	1 947 547
NE	0	94 509	1 048 889	1 143 398	1 312 069	1 447 948	1 723 734	4 483 751
OH	856 162	2 335 966	4 257 681	7 449 809	6 417 644	9 783 661	11 245 345	27 446 650
OK	0	0	930 086	930 086	2 171 459	2 527 813	3 477 119	8 176 391
SD	0	16 437	425 366	441 803	647 575	672 564	767 099	2 087 238
TN	549 963	1 139 206	1 978 261	3 667 430	2 653 669	3 848 041	5 671 575	12 173 285
TX	21 259	607 815	3 077 067	3 706 141	5 681 260	10 697 433	21 346 927	37 725 620
WI	37 744	702 291	2 017 504	2 757 539	2 900 023	4 134 233	5 307 661	12 341 917
Total	4 145 428	16 145 653	42 408 201	62 699 282	61 882 162	88 713 864	120 695 222	271 291 248

and 3) real-time response to tornadoes. Communication in real time can be improved by developing new smartphone applications for social media. This development can be prototyped and targeted in the local regions of highest DPI values. Such applications could also have spin-off value to other types of natural hazards (such as tsunamis and flash floods).

The success of efforts to date in a growing and expanding population has been established as evidenced by the DPI trend in Era B. Maintaining a future record

TABLE A3. The numerator term in Eq. (1): total tornado deaths scaled by 10^4 and normalized per unit land area rounded to the nearest whole number.

State	Period I	Period II	Period III	Era A total	Period IV	Period V	Period VI	Era B total
AL	0.38	5.41	25.39	31.18	55.96	16.47	31.56	103.99
AR	0.00	0.59	24.19	24.78	66.56	18.92	10.76	96.24
GA	0.00	5.17	25.38	30.55	35.65	5.84	9.06	50.55
IA	0.00	9.06	26.82	35.88	5.94	3.87	2.00	11.81
IL	0.76	11.47	28.51	40.74	39.92	10.43	5.22	55.57
IN	0.32	4.85	8.51	13.68	41.49	22.09	6.57	70.15
KS	0.00	2.69	13.08	15.77	10.06	8.31	2.83	21.20
KY	0.10	1.96	14.47	16.53	19.07	9.97	4.40	33.44
LA	0.09	0.54	25.56	26.19	26.10	11.26	3.22	40.58
MI	0.00	0.27	5.33	5.60	1.37	15.98	0.61	17.96
MN	0.00	0.73	12.41	13.14	6.40	3.93	0.92	11.25
MO	0.00	2.86	29.71	32.57	35.16	8.20	13.99	57.35
MS	4.11	3.95	34.72	42.78	65.83	27.81	12.1	105.74
ND	0.00	0.00	1.45	1.45	1.79	1.23	0.17	3.19
NE	0.00	0.45	10.05	10.50	3.57	2.46	0.35	6.38
OH	1.32	9.92	4.06	15.30	14.36	14.93	3.50	32.79
OK	0.00	0.00	19.14	19.14	38.33	10.86	8.39	57.58
SD	0.00	0.00	2.70	2.70	2.44	0.56	0.36	3.36
TN	0.47	1.97	19.94	22.38	29.59	15.08	17.32	61.99
TX	0.00	0.03	8.10	8.13	10.91	6.10	2.26	19.27
WI	0.00	9.05	14.61	23.66	6.70	5.13	2.07	13.90
Total	7.55	70.97	354.13	432.65	517.20	219.43	137.66	874.29

TABLE A4. The denominator term in Eq. (1): normalized population per state scaled by 10^4 and rounded to the nearest whole number.

State	Period I	Period II	Period III	Era A total	Period IV	Period V	Period VI	Era B total
AL	21 707	69 746	138 856	230 309	198 718	260 503	337 086	796 307
AR	3684	29 307	98 159	131 150	135 346	146 587	196 868	478 801
GA	31 352	71 569	149 065	251 986	200 695	292 926	546 306	1 039 927
IA	1925	50 028	144 869	196 822	169 976	192 181	204 224	566 381
IL	15 690	119 622	331 519	466 831	507 475	719 057	848 029	2 074 561
IN	36 559	144 186	265 767	446 512	348 186	520 365	653 232	1 521 783
KS	0	11 448	70 509	81 957	85 645	102 773	126 106	314 524
KY	59 456	114 242	203 590	377 288	256 683	314 961	395 140	966 784
LA	18 892	58 063	123 457	200 412	188 624	308 700	396 316	893 640
MI	6190	55 578	170 344	232 112	313 833	553 199	661 276	1 528 308
MN	29	12 222	81 478	93 729	124 602	173 386	236 445	534 433
MO	10 689	68 263	166 611	245 563	187 786	250 946	312 546	751 278
MS	15 240	61 288	125 464	201 992	163 894	186 905	229 370	580 169
ND	0	292	19 ,991	20 283	35 898	35 277	37 802	108 977
NE	0	4750	52 715	57 465	65 942	72 771	86 631	225 344
OH	80 901	220 730	402 317	703 948	606 416	924 478	1 062 596	2 593 490
OK	0	0	52 352	52 352	122 226	142 284	195 718	460 228
SD	0	837	21 664	22 501	32 981	34 253	39 068	106 302
TN	51 496	106 669	185 234	343 399	248 476	360 310	531 056	1 139 842
TX	314	8984	45 479	54 777	83 969	158 109	315 509	557 587
WI	2691	50 068	143 832	196 591	206 749	294 738	378 394	879 881
Total	356 815	1 257 892	2 993 272	4 607 979	4 284 120	6 044 709	7 789 718	18 118 547

of DPI is also of value in documenting the success of future efforts to reduce tornado fatalities.

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APPENDIX

Raw Data for Deaths and Population for Each State for All Six Periods

Table A1 shows total tornado deaths per state for each of the six periods. Table A2 gives total average population per state for each of the six periods. Table A3 contains the numerator term in Eq. (1), with total tornado deaths scaled by 10^4 and normalized per unit land area rounded to the nearest whole number. In a similar way, Table A4 has the denominator term in Eq. (1), with normalized population per state scaled by 10^4 and rounded to the nearest whole number.

REFERENCES

Agee, E., and S. Childs, 2014: Adjustments in tornado counts, F-scale intensity, and path width for assessing significant tornado destruction. *J. Appl. Meteor. Climatol.*, **53**, 1494–1505, https://doi.org/10.1175/JAMC-D-13-0235.1.

——, J. Larson, S. Childs, and A. Marmo, 2016: Spatial redistribution of U.S. tornado activity between 1954 and 2013. *J. Appl. Meteor. Climatol.*, **55**, 1681–1697, https://doi.org/10.1175/JAMC-D-15-0342.1.

Ashley, W. S., 2007: Spatial and temporal analysis of tornado fatalities in the United States: 1880–2005. *Wea. Forecasting*, **22**, 1214–1228, https://doi.org/10.1175/2007WAF2007004.1.

——, and S. M. Strader, 2016: Recipe for disaster: How the dynamic ingredients of risk and exposure are changing the tornado disaster landscape. *Bull. Amer. Meteor. Soc.*, **97**, 767–786, https://doi.org/10.1175/BAMS-D-15-00150.1.

Borden, K. A., and S. L. Cutter, 2008: Spatial patterns of natural hazards mortality in the United States. *Int. J. Health Geogr.*, **7**, 64, https://doi.org/10.1186/1476-072X-7-64.

Boruff, B., J. Easoz, S. Jones, H. Landry, J. Mitchem, and S. Cutter, 2003: Tornado hazards in the United States. *Climate Res.*, **24**, 103–117, https://doi.org/10.3354/cr024103.

Bradford, M., 1999: Historical roots of modern tornado forecasts and warnings. *Wea. Forecasting*, **14**, 484–491, https://doi.org/10.1175/1520-0434(1999)014<0484:HROMTF>2.0.CO;2.

Brooks, H. E., and C. A. Doswell III, 2002: Deaths in the 3 May 1999 Oklahoma City tornado from a historical perspective. *Wea. Forecasting*, **17**, 354–361, https://doi.org/10.1175/1520-0434(2002)017<0354:DITMOC>2.0.CO;2.

——, G. W. Carbin, and P. T. Marsh, 2014: Increased variability of tornado occurrence in the United States. *Science*, **346**, 349–352, https://doi.org/10.1126/science.1257460.

Concannon, P. R., H. E. Brooks, and C. A. Doswell III, 2000: Climatological risk of strong to violent tornadoes in the United States. *Second Symp. on Environmental Applications*, Long Beach, CA, Amer. Meteor. Soc., 9.4, https://ams.confex.com/ams/annual2000/techprogram/paper_6471.htm.

Dixon, R. W., and T. W. Moore, 2012: Tornado vulnerability in Texas. *Wea. Climate Soc.*, **4**, 59–68, https://doi.org/10.1175/WCAS-D-11-00004.1.

Edwards, R., and L. R. Lemon, 2002: Proactive or reactive? The severe storm threat to large venues. Preprints, *21st Conf. on Severe Local Storms*, San Antonio, TX, Amer. Meteor. Soc., 7.1, https://www.spc.noaa.gov/publications/edwards/lrgvenue.pdf.

——, J. G. LaDue, J. T. Ferree, K. Scharfenberg, C. Maier, and W. L. Coulbourne, 2013: Tornado intensity estimation: Past, present, and future. *Bull. Amer. Meteor. Soc.*, **94**, 641–653, https://doi.org/10.1175/BAMS-D-11-00006.1.

Elsner, J. B., S. C. Elsner, and T. H. Jagger, 2015: The increasing efficiency of tornado days in the United States. *Climate Dyn.*, **45**, 651–659, https://doi.org/10.1007/s00382-014-2277-3.

Finley, J. P., 1884: Report on the character of six hundred tornadoes. Professional Papers of the Signal Service No. 7, 28 pp., https://babel.hathitrust.org/cgi/pt?id=nnc1.cu04694546;view=1up;seq=1.

Fricker, T., J. B. Elsner, and T. H. Jagger, 2017: Population and energy elasticity of tornado casualties. *Geophys. Res. Lett.*, **44**, 3941–3949, https://doi.org/10.1002/2017GL073093.

Galway, J. G., 1985: J. P. Finley: The first severe storms forecaster. *Bull. Amer. Meteor. Soc.*, **66**, 1389–1395, https://doi.org/10.1175/1520-0477(1985)066<1389:JFTFSS>2.0.CO;2.

Golden, J. H., and C. R. Adams, 2000: The tornado problem: Forecast, warning, and response. *Nat. Hazards Rev.*, **1**, 107–118, https://doi.org/10.1061/(ASCE)1527-6988(2000)1:2(107).

Grazulis, T. P., 1993: *Significant Tornadoes 1680–1991: A Chronology and Analysis of Events*. Environmental Films, 1326 pp.

Hall, S. G., and W. S. Ashley, 2008: The effects of urban sprawl on the vulnerability to a significant tornado impact in northeastern Illinois. *Nat. Hazards Rev.*, **9**, 209–219, https://doi.org/10.1061/(ASCE)1527-6988(2008)9:4(209).

Huff, F. A., H. W. Hiser, and S. G. Bigler, 1954: Study of an Illinois tornado using radar, synoptic weather and field survey data. Illinois State Water Survey Investigation Rep. 22, 73 pp.

Maddox, R., and C. Crisp, 1999: The Tinker AFB tornadoes of March 1948. *Wea. Forecasting*, **14**, 492–499, https://doi.org/10.1175/1520-0434(1999)014<0492:TTATOM>2.0.CO;2.

Standohar-Alfano, C. D., and J. W. van de Lindt, 2015: Empirically based probabilistic tornado hazard analysis of the United States using 1973–2011 data. *Nat. Hazards Rev.*, **16**, 04014013, https://doi.org/10.1061/(ASCE)NH.1527-6996.0000138.

Strader, S. M., and W. S. Ashley, 2018: Fine-scale assessment of mobile home tornado vulnerability in the central and southeast U.S. *Wea. Climate Soc.*, **10**, 797–812, https://doi.org/10.1175/WCAS-D-18-0060.1.

——, ——, T. J. Pingel, and A. J. Krmenec, 2017: Projected 21st century changes in tornado exposure, risk, and disaster potential. *Climatic Change*, **141**, 301–313, https://doi.org/10.1007/s10584-017-1905-4.

Verbout, S. M., H. E. Brooks, L. M. Leslie, and D. M. Schultz, 2006: Evolution of the U.S. tornado database: 1954–2003. *Wea. Forecasting*, **21**, 86–93, https://doi.org/10.1175/WAF910.1.

Widen, H. M., T. Fricker, and J. B. Elsner, 2015: New methods in tornado climatology. *Geogr. Compass*, **9**, 157–168, https://doi.org/10.1111/gec3.12205.