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

by

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Abstract

The record of tornado fatalities in the U.S. for over two centuries (1808-2017) along with the 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 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 sub-intervals, *Era A* (1808-1915) and *Era B* (1916-2017) where each 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 define the respective periods. A death per population index (DPI) is used to evaluate the 21 states in each era, which shows the 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 even 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. 2014; 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 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 define the most tornado-prone regions based on tornado deaths. It is documented that significant tornadoes, (E)F2-(E)F5, are responsible for the large majority of tornado fatalities (e.g. see 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 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 methodology 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 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°W to 105°W that extends from the Gulf Coast to the Canadian border. This analysis approach has also helped define two eras that typify the relationship between 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 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 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. Tornado Risk Assessment by Standohar-Alfano and van de Lindt (2015) has provided a probabilistic tornado hazard index for the U.S. (which can be extended to other geographical locations) based on a data record analysis from 1974-2011. Boruff et al. (2003) have examined the frequency of tornado hazards for the period 1950-1999, as well as a search for geographical shifts in spatial frequency. Discussion of tornado forecast, warning and response was provided by Golden and Adams (2000), which has continually improved for nearly two decades, along with an increased focus on vulnerability due to 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 1955-2016. Future work is expected to pursue in more detail the role of socio-economic 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 for hazard assessment and risk analysis, and no tornado forecast, warning and response, and no supporting technology (a century that is in total contrast to Era B).

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*: 1808-1843, *Period II*: 1844-1879, *Period III*: 1880-1915, *Period IV*: 1916-1949, *Period V*: 1950-1983, and *Period VI*: 1984-2017. Criteria and discussion will follow that help 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 Central Plains 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 northeast corner of Arkansas during the last decade of the 20th century.

II. 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 John P. Finley (e.g. see 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 (1916-1949). It is noted that these have lengths of 36 years 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 I, but it was desirable to have 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 methodologies 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 Plains. Prior to this era the first recorded tornado death was 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 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" even though 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, 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 (1808-1843) and Period II (1844-1879)*

As noted above, the start and end of these periods have been defined (see Table 1), which 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 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 was a sufficient number of people located in the region). At the beginning of Period I there were only 4 states and multiple territories, which by the end of Period II 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)*

Due to the efforts by John P. Finley the third period brought into existence the concept of meteorologists keeping tornado records, and the effort to seek out volunteers and 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 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 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.

3) *Period IV (1916-1949)*

In 1916 the U.S. Weather Bureau became the official collection agency for tornado reports, which 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 USWB lifted the ban on use of the word "tornado" and later moved to the Department of Commerce in 1940. Positive spinoffs from WWII 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).

4) *Period V (1950-1983)*

This period begins with the start of the modern tornado record, as well as the USWB 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 SELS, NSSL, and the 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 IL on April 9, 1953 (see 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.

5) *Period VI (1984-2017)*

As evident in Table I, scientific and technological progress continued, highlighted by the introduction of Doppler radar allowing for the detection of rotational velocity in storms that can identify mesoscale vortices and the potential development of tornadoes. NSSFC is renamed the Storm Prediction Center and subsequently moves from Kansas City to Norman, OK. This co-location 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 including portable Doppler radar. Both radar and satellite technology also continued to advance with the dual-pol Doppler (and the detection of the tornado debris signature), as well as the extremely high resolution imagery of the latest GOES satellite series.

III. Methodology

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 ten-year basis (1790 to 2010) including an estimate for 2017. Population average was made (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. In order 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 death per population index (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 (as the land area of each state cancels out):

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

$$\textbf{DPI} = \textbf{(Total Deaths for the Period)}_{\textbf{state}} \ / \ \textbf{(Average Population for the Period)}_{\textbf{state}} . \qquad (2)$$

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 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. Appendix A however, contains Tables A1-A4 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 also in Eq.(1). 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).

IV. Results and Conclusions

Era A has been defined as a time of small yet a westward migrating population with little to no scientific knowledge of tornadoes and virtually no technology or communications capability to warn the public. Figs. 2-4 show the average DPI x 10^4 for each state in Periods I, II, and III. In Fig.2 only two states (Mississippi and Illinois) were above the non-zero DPI average, which is likely due to having a 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. Fig.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 OK, MS and AR had the highest DPI values. It appears that OK 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 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 technology were also advancing rapidly, resulting in a steadily decreasing DPI value for all three time periods in Era B. Figs. 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. Fig. 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 in the 102-year long Era B. These states ranked in order of highest DPI value are Arkansas (1st), Mississippi (2nd), Alabama (3rd), and Oklahoma (4th). 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 more 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 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 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 (based on this event). Safety offered by the bank vault in the Moore, OK 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 FEMA 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, based on a comparison of Central and Southeast U.S. (which was extended down to a county-size scale for Kansas and Alabama). This fine scale 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 21st 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 in the past 102 years (1916-2017), through each of three successive 34-year 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 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). Philosophically, 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 socio-demographic changes. It is further noted, however, that hazard mortality data did not exist in Era A and has 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) enhances 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 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 fine-scale assessment reported by Strader and Ashley (2018) could be done for the DPI index 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: a) long-term preparation, b) the day of the tornado threat, and c) real-time response to tornadoes. Communication in real-time can be improved by developing new smart-phone applications for social media. This 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 based on the DPI trend in Era B. Maintaining a future record of DPI is also of value in documenting the success of future efforts to reduce tornado fatalities.

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Appendix A

Raw Data for Deaths and Population for each State for all Six Periods

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

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

Table A3. Numerator term in Eq.(1). Total tornado deaths scaled by 10^4 and normalized per unit land area rounded to the nearest whole number.

Table A4. Denominator term in Eq.(1). Normalized population per state scaled by 10^4 and rounded to the nearest whole number.

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Table 1: The six time periods selected for this study as well as some of the notable events. including development and improvement in weather prediction and technology.

Time Period	Some Notable Events
I (1808 - 1843)	**1808** – Year selected to establish three consecutive 36-year periods, based on the defined critical notable events that established Period III and Period IV
II (1844 - 1879)	**1844** – Year selected to establish three consecutive 36-year periods 1869 – Cleveland Abbe appointed chief meteorologist in the Signal Service 1870 – Weather service established in the Department of War 1877 – John Finley enlisted in the Signal Service (Galway 1985)
III (1880 - 1915)	**1880** – 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 – U.S. Weather Bureau established in the Department of Agriculture
IV (1916 - 1949)	**1916** – Weather Bureau becomes the official collection agency for tornado reports 1919 – American Meteorological Society formed 1938 – Ban on the use of "tornado" in weather products removed by the USWB 1940 – Weather Bureau moved to the Department of Commerce 1945 – Electronic computer ENIAC; first experimental weather prediction 1950 1948 – Tornado forecast by Fawbush and Miller (see Maddox and Crisp, 1999)
V (1950 - 1983)	**1950** – Start of modern tornado record 1950 – USWB lifted the ban on issuing tornado warnings to the public 1952 – Severe Local Storms (SELS) unit established; First public tornado forecast 1953 – First detected radar hook echo by Illinois State Water Survey, Champaign 1957 – WSR57 Weather Serv. Radar (used by Nat'l Severe Storms Project 1962) 1960 – TIROS-1 first weather satellite (polar-orbiting) 1964 – National Severe Storms Lab (NSSL) established in Norman, OK 1966 – SELS became National Severe Storms Forecast Center (NSSFC), 1970 – U.S. Weather Bureau renamed National Weather Service 1971 – Fujita Tornado Intensity Scale introduced (Edwards et al. 2013) 1975 – Geosynchronous Orbiting Earth Satellite (GOES-1) launched into orbit 1982 – Weather Channel debut
VI (1984 - 2017)	**1984** – (Year selected to establish three consecutive 34-year periods) 1988 – NEXRAD (WSR-88D) Doppler radar, implemented in the 1990s. 1995 – NSSFC renamed Storm Prediction Center (SPC) 1997 – SPC moves from Kansas City to Norman, OK 1999 – NSSL discovers tornado debris signature with experimental dual-pol radar 2007 – Fujita Scale 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 which became operational GOES-16

APPENDIX A

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	**1,364**
AR	0	8	326	**334**	897	255	145	**1,297**
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	**1,021**
MS	50	48	422	**520**	800	338	147	**1,285**
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	**1,304**
WI	0	127	205	**332**	94	72	29	**195**
TOTAL	**90**	**962**	**5,538**	**6,590**	**76,17**	**3,251**	**1,994**	**12,862**

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	5,215	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**

Table A3: 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: 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	3,684	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	1,925	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	6,190	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	4,750	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	8,984	45,479	**54,777**	83,969	158,109	315,509	**557,587**
WI	2,691	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**

Figure Legends

Fig.1. The 21-state region of the U.S. selected for study.

Fig.2. Average DPI per state for Period I (1808-1843) 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 average for tornado fatalities.

Fig.3. Average DPI per state for Period II (1844-1879) 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 average for tornado fatalities.

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 average for tornado fatalities.

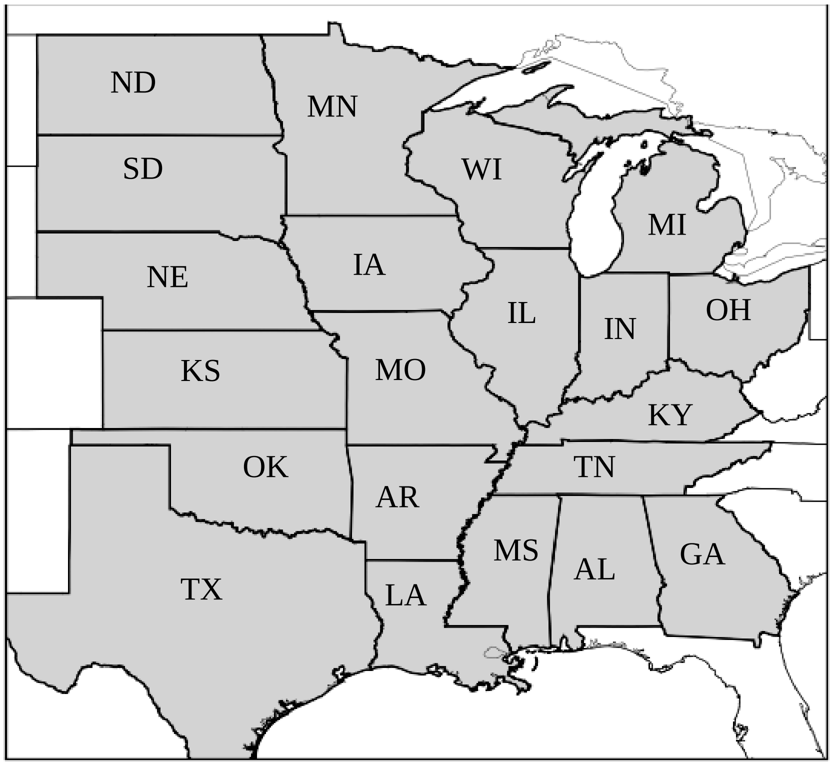
Fig.5. Average DPI per state for Period IV (1916-1949) scaled by 10^4. The mean DPI for all 21 states is 1.41, with a total of 6 states above average for tornado fatalities.

Fig.6. Average DPI per state for Period V (1950-1983) scaled by 10^4. The mean DPI for all 21 states is 0.45, with a total of 5 states above 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 average for tornado fatalities.

Fig. 8. Identification of states with highest frequency of tornado deaths 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-year intervals (*Era A*) represented by Periods I, II, and III, and three successive 34-year intervals (*Era B*) represented by Periods IV, V, VI, plotted as time-centered points. The exponential decline in Era B (projected to be 0.05 by the year 2040) depicts that even with a population growth rate, the tornado death rate is not as fast, or even decreasing, versus population growth (providing there are continued improvements in prediction, detection and warning, safety practices, and associated technological enhancements).



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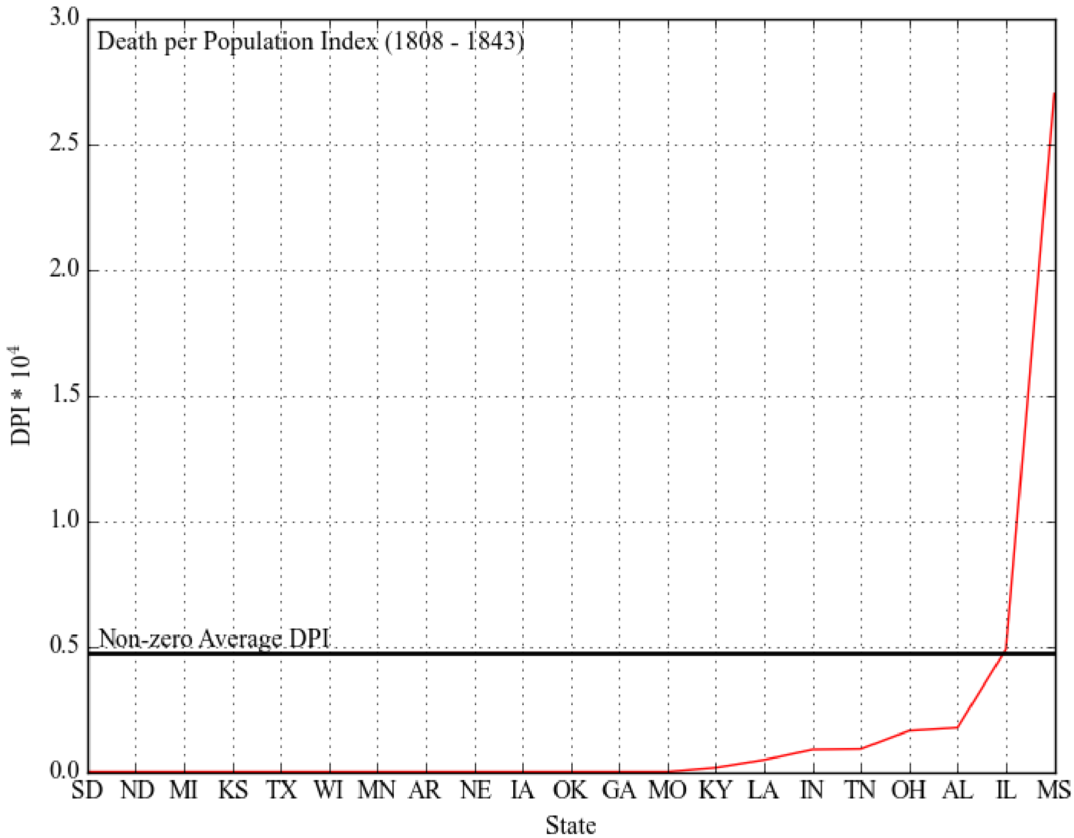

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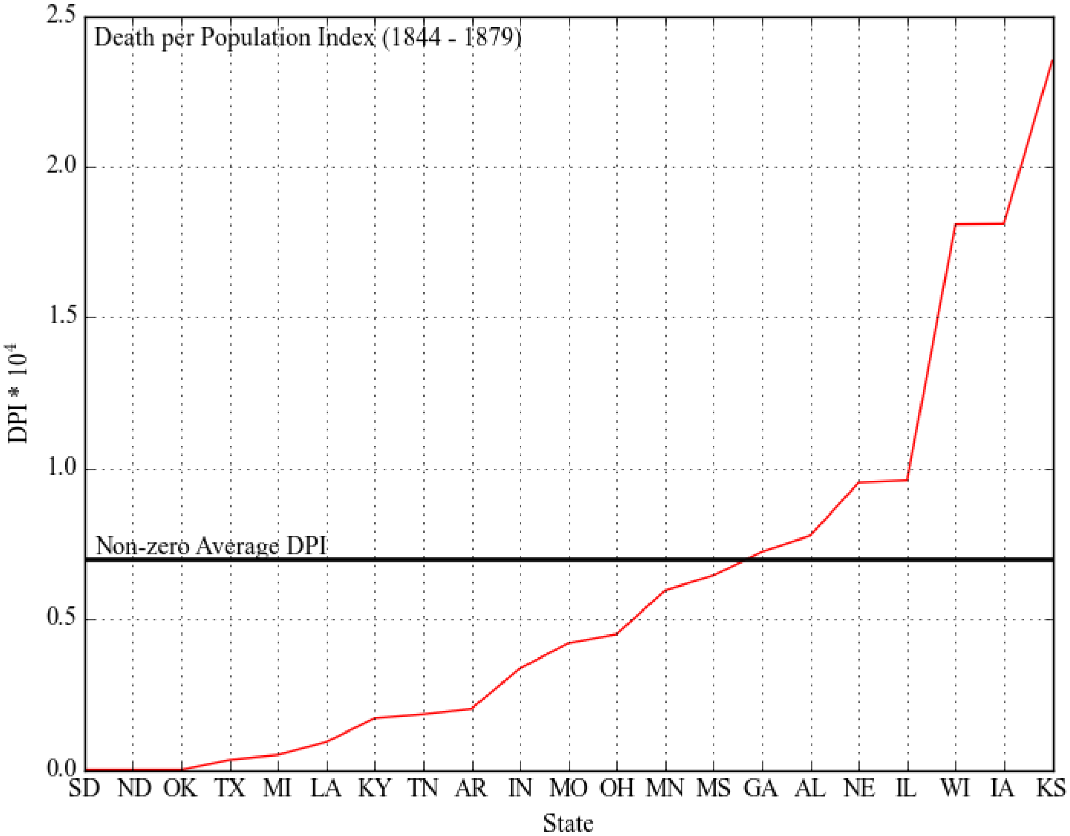


Fig.3. Average DPI per state for Period II (1844-1879) scaled by 10^4. The mean DPI for 18 of the 21 states (excluding the three zero value states) is 0.70, with 7 states above average for tornado fatalities.

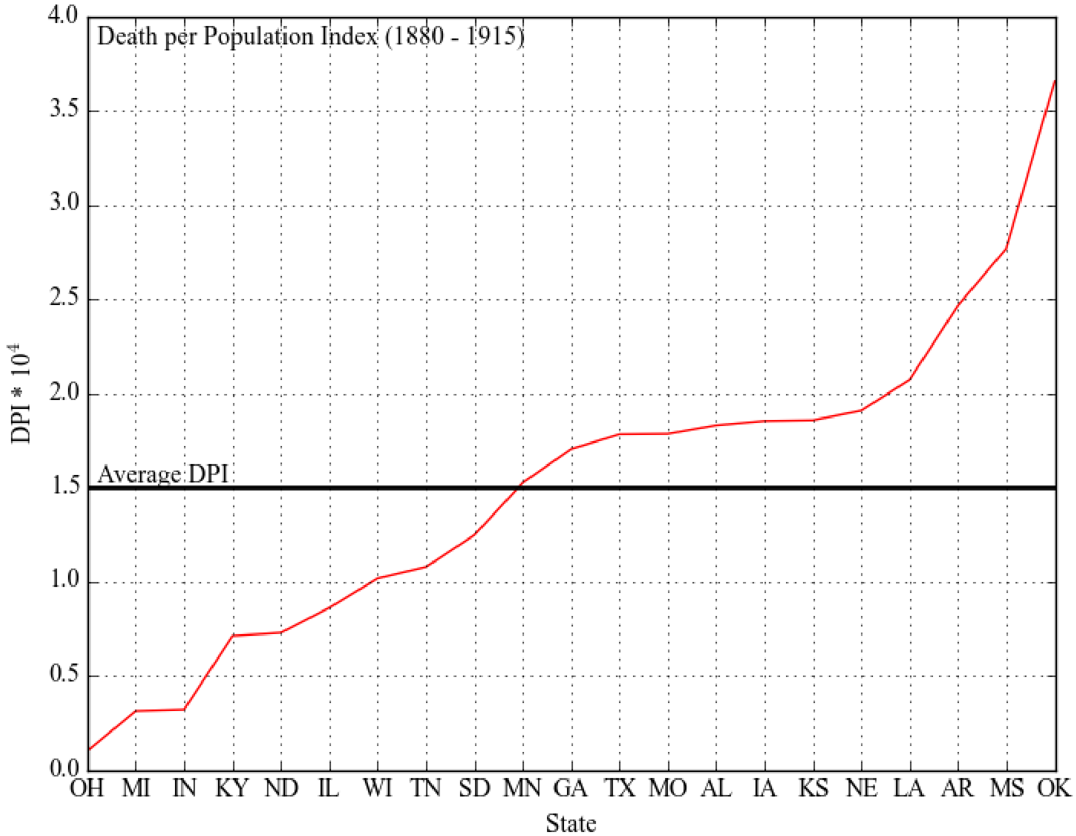


Fig.4. Average DPI per state for Period III (1880-1915) scaled by 10^4. The mean DPI for all 21 states is 1.50, with a total of 12 states above average for tornado fatalities.

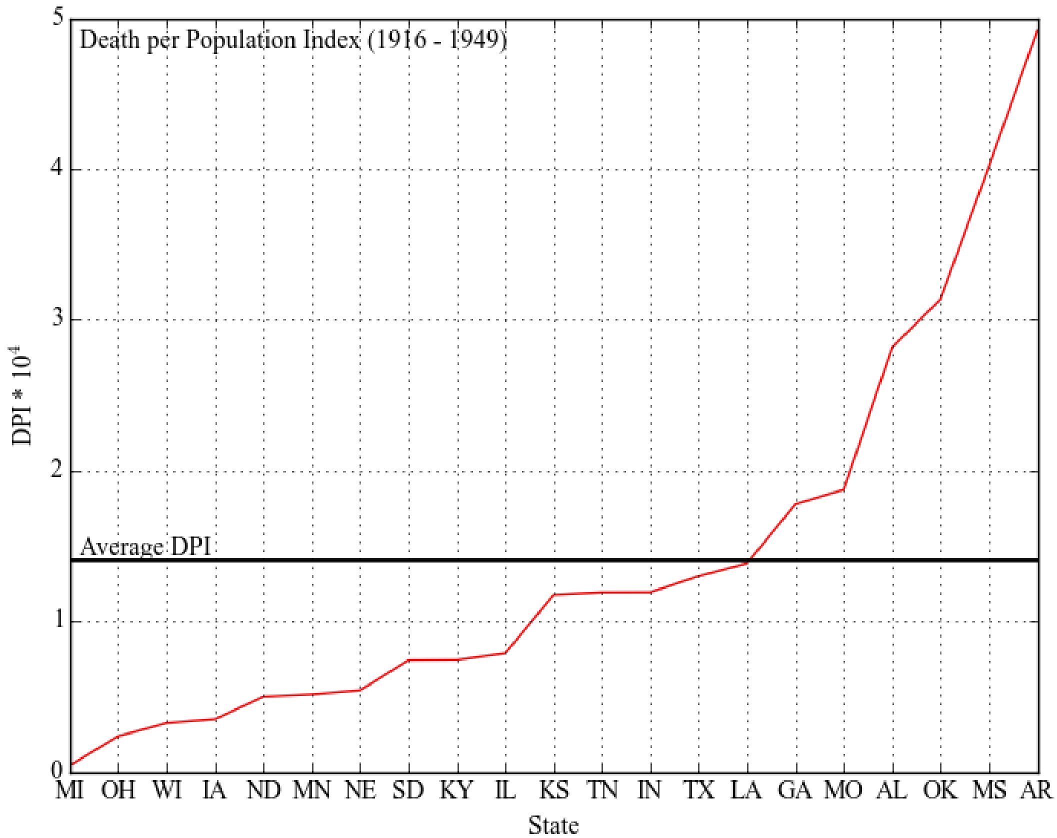


Fig.5. Average DPI per state for Period IV (1916-1949) scaled by 10^4. The mean DPI for all 21 states is 1.41, with a total of 6 states above average for tornado fatalities.

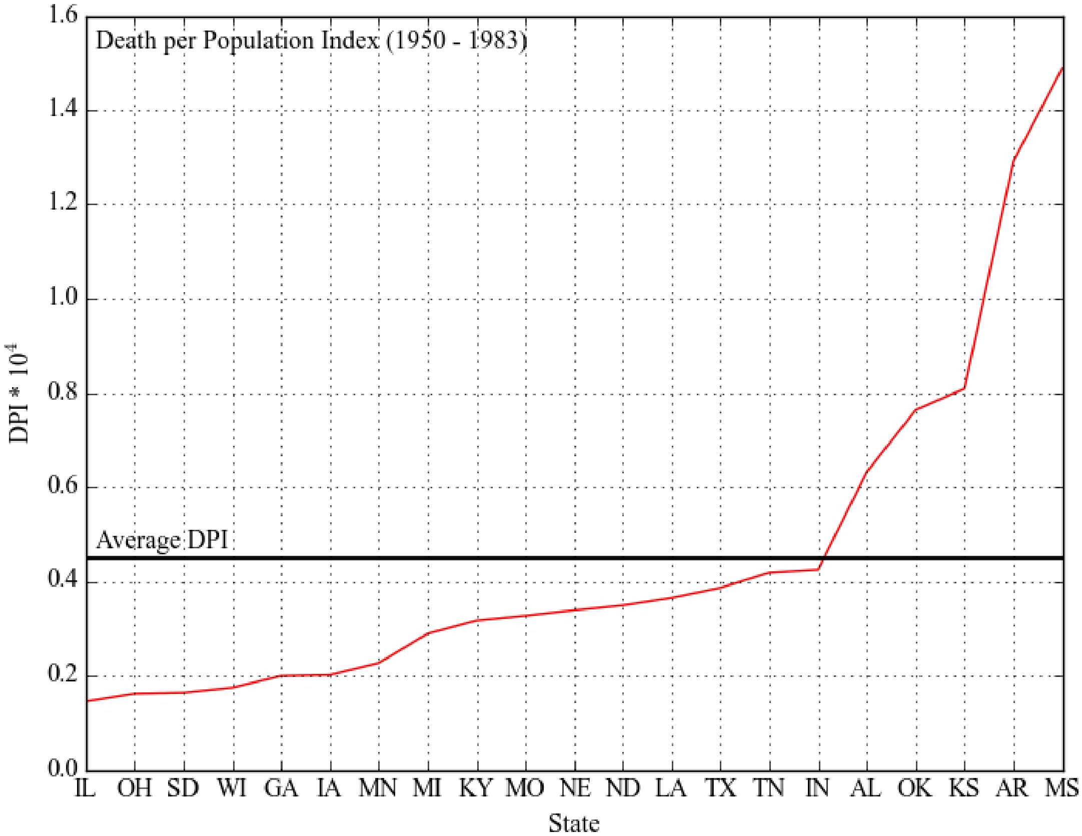


Fig.6. Average DPI per state for Period V (1950-1983) scaled by 10^4. The mean DPI for all 21 states is 0.45, with a total of 5 states above average for tornado fatalities.

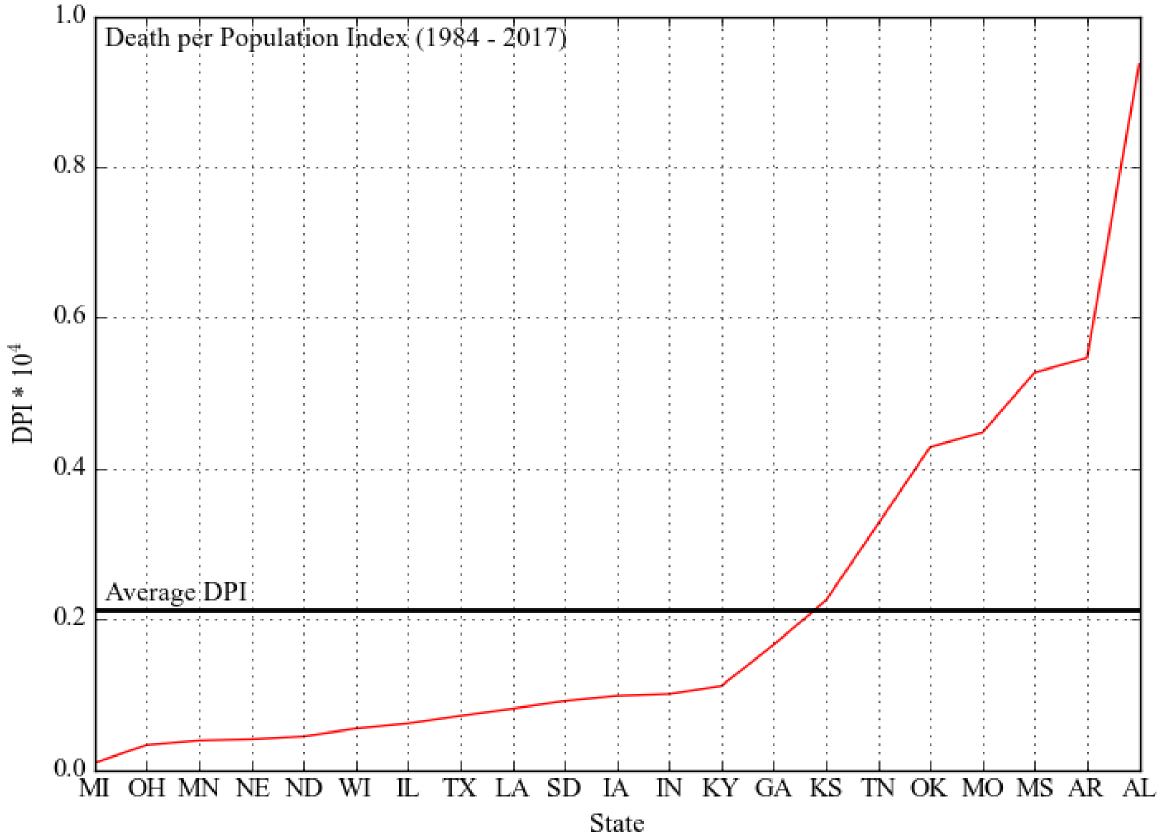
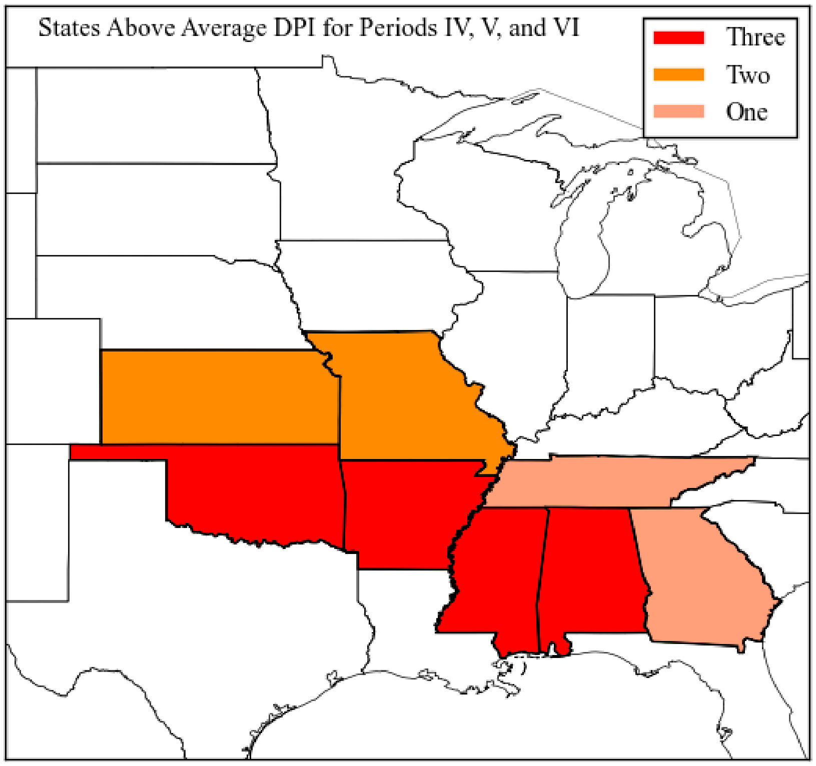


Fig.7. Average DPI per state for Period VI (1984-2017) scaled by 10^4. The mean DPI for all 21 states is 0.21, with a total of 7 states above average for tornado fatalities.



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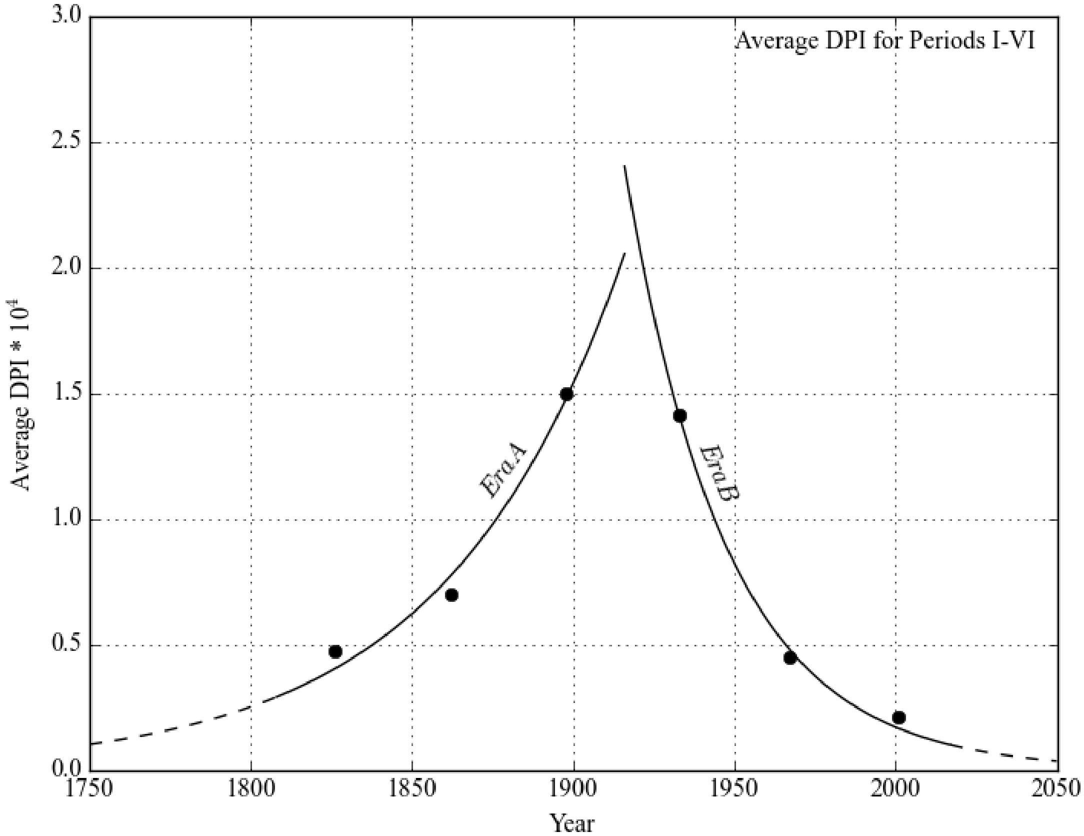

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