Tornado Fatalities in Context: 1995–2018

TYLER FRICKER[a] AND COREY FRIESENHAHN[b]

[a] *University of Louisiana Monroe, Monroe, Louisiana*
[b] *Texas A&M University, College Station, Texas*

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ABSTRACT: Tornadoes account for the third highest average annual weather-related fatality rate in the United States. Here, tornado fatalities are examined as rates within the context of multiple physical and social factors using tornado-level information including population and housing units within killer tornado damage paths. Fatality rates are further evaluated across annual, monthly, and diurnal categories as well as between fatality locations and across age and sex categories. The geographic distribution of fatalities is then given by season, time of day, and residential structures. Results can be used by emergency managers, meteorologists, and planners to better prepare for high-impact (i.e., fatality) events and used by researchers as quantitative evidence to further investigate the relationship between tornadoes, climate, and society.

SIGNIFICANCE STATEMENT: In the United States, tornadoes have killed around 70 people per year, on average, over the past few decades. While previous work has focused on the number or location of tornado fatalities, here fatalities are evaluated through rates at both the population and household level across a number of physical and social factors. Fatality rates are highest during the cold season, at night, and for mobile homes and older adults. Across space, fatalities appear to be increasingly concentrated throughout the mid-South and Southeast relative to previous studies. These results can be used to better prepare for tornado fatality events or to provide further quantitative evidence to ground future tornado fatality research.

KEYWORDS: Tornadoes; Climatology; Societal impacts

1. Introduction

Tornadoes have killed around 70 people, on average, per year in the United States over the past 30 years. In fact, tornadoes account for the third highest average annual weather-related fatality rate in the country, trailing only extreme heat and floods. Even in years with below average numbers of killer tornadoes, the loss of life can devastate and impact communities throughout the country. For example, 2018 was the least active killer tornado season over the past 24 years and yet 10 people still lost their lives.

Some previous studies have focused on the number and location of tornado fatalities (Grazulis 1990; Hammer and Schmidlin 2000; Ashley 2007; Fricker et al. 2017b; Paulikas and Schmidlin 2017; Agee and Taylor 2019). For example, Grazulis (1990) provides a historical narrative of significant and killer tornado reports since the late nineteenth century, and Hammer and Schmidlin (2000) and Paulikas and Schmidlin (2017) detail vehicle-related tornado fatalities over the periods 1900–98 and 1991–2015, respectively. Ashley (2007) examines spatial and temporal aspects of all tornado fatalities between 1880 and 2005, while Fricker et al. (2017b) use a dasymetric method to map all tornado fatalities across the most tornado-prone region of the United States over the period 1955–2016. More recently, Agee and Taylor (2019) identify which states have been the most impacted by tornado fatalities dating back to 1808 using a death per population index. Consistency in the results of these works can be seen in the spatial extent of tornado fatalities, which have occurred in the largest numbers in the mid-South and Southeast United States, most notably in the states of Alabama, Arkansas, and Mississippi.

Other studies have focused on the identification of risk factors associated with tornado fatalities (Kilijanek and Drabek 1979; Simmons and Sutter 2005, 2008, 2009; Donner 2007; Ashley et al. 2008; Dixon and Moore 2012; Donner et al. 2012; Ashley et al. 2014; Lim et al. 2017; Fricker et al. 2017a; Elsner et al. 2018; Masoomi and van de Lindt 2018; Fricker and Elsner 2019; Strader et al. 2021). For example, Simmons and Sutter (2005, 2008, 2009), Lim et al. (2017), and Masoomi and van de Lindt (2018) use regression models to explain the impact different physical, socioeconomic, and demographic factors have on fatalities. Fricker et al. (2017a) and Elsner et al. (2018) use similar regression techniques to explain the relative impact wind energy—estimated energy dissipation at the surface—and population density have on casualties—including fatalities—while Fricker and Elsner (2019) evaluate the residuals of a regression model to identify communities that are impacted by unusually devastating tornadoes. Kilijanek and Drabek (1979), Donner (2007), Ashley et al. (2008, 2014), Dixon and Moore (2012), Donner et al. (2012), and Strader et al. (2021) use other qualitative, geographic, and statistical methods to identify patterns between risk factors and tornado fatalities. Results of these works show that the number of tornado fatalities increases with tornado strength, population density, percentage of mobile homes, and the number of older adults (age 65+) in an area. Additionally, results of these works show that nocturnal tornadoes—those occurring between

Corresponding author: Tyler Fricker, tfricker@ulm.edu

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sunset and sunrise—are more than twice as likely to result in a tornado fatality than tornadoes occurring during the day, and that Southeast National Weather Service (NWS) county warning areas are the most prone to tornado fatalities because of the juxtaposition of tornado risk and high social vulnerability.

Absent from these previous studies is a fine-scale understanding of the rate of tornado fatalities, that is, the number of tornado fatalities per capita or per housing unit. To this point, most of our knowledge related to fine-scale fatality rates comes from surveys of high-impact tornado events. For example, Biddle (2007) examines the 1999 Oklahoma City, Oklahoma, tornado that resulted in 36 fatalities and finds that ~50 000 people and 4300 housing units were impacted by the tornado, which corresponds to a per-capita fatality rate of 0.072% and a per–housing unit fatality rate of 0.84%. Similarly, Kuligowski et al. (2014) investigate the 2011 Joplin, Missouri, tornado that resulted in 158 fatalities and find that an estimated 20 820 people and 7500 housing units were impacted by the tornado, corresponding to a per-capita fatality rate of 0.76% and a per–housing unit fatality rate of 2.1%. More recently, Fricker (2020a) uses tornado-level socioeconomic and demographic estimates to investigate tornado casualty rates by exposed person—those within the damage path—and exposed housing unit—those within the damage path—in the United States. Results show that in casualty-producing tornadoes—those that produce at least one injury or death—over the period 1995–2016, the estimated per-capita fatality rate in the United States is 0.15% and the estimated per–housing unit fatality rate in the United States is 0.36%. These fatality rates, however, exist at a general level, which means that individual fatality rates at any Fujita (F) or enhanced Fujita (EF) scale rating, for any fatality location (e.g., mobile or permanent home), across any diurnal or seasonal scale remain unknown.

The usefulness of fatality rates in the prediction of tornado impacts can be linked to the simplicity in which they exist. Knowing the rate at which people are killed in tornadoes at the per-capita or per–housing unit level allows emergency managers, meteorologists, or planners to think about worst-case or what-if scenarios (Clarke 2005; Wurman et al. 2007; Antonescu et al. 2018) in their local communities. For example, using the fatality rates found in Fricker (2020a), if an emergency manager works for a city of 50 000 people with 10 000 housing units and predicts the worst-case scenario for any individual tornado is the impact—or exposure—of one-half of the population and one-third of the housing units, they would estimate, on average, that the tornado would result in 38 fatalities ($25\,000 \times 0.0015$) at the per-capita level or 12 fatalities (3333×0.0036) at the per–housing unit level. In addition, more detailed—or appropriate—fatality estimates could be made for communities through an overlay analysis of historical tornado paths and current population or housing unit data. In this sense, communities could plan and prepare for what fatality events might look like if similar tornadoes were to impact the area again.

Here we build on the work of Fricker (2020a) as a means to estimate tornado fatality rates in killer tornadoes—those that produce at least one death—within the contiguous United States over the period 1995–2018. More specifically, we expand previous estimates of tornado fatality rates along multiple physical and social factors—including fatality location, demographic profiles, and year, month, and hour of occurrence—existing within a spatiotemporal context. Furthermore, we restrict this analysis to only those tornadoes that produce at least one death, which we argue provides a more reasonable sample of tornado fatality events than all casualty-producing tornadoes with which we can investigate fatality rates. Ultimately, the goal of this work is to create a more complete foundational knowledge of tornado fatalities—beyond total counts—in the United States, with the ability to establish patterns at both the population and household level.

TABLE 1. Direct fatality location table. Redrafted from Table 3 in National Weather Service (2021).

Location abbreviation	Location description
BF	Ball field
BO	Boating
BU	Business
CA	Camping
CH	Church
EQ	Heavy equipment/construction
GF	Golfing
IW	In water
LS	Long span roof
MH	Mobile/trailer home
OT	Other/unknown
OU	Outside/open areas
PH	Permanent home
PS	Permanent structure
SC	School
TE	Telephone
UT	Under tree
VE	Vehicle and/or towed trailer

2. Data and methods

Tornado reports for all killer tornadoes—tornadoes that cause at least one fatality—over the period 1995–2018 are obtained from the U.S. Storm Prediction Center's (SPC) database (https://www.spc.noaa.gov/gis/svrgis/). These reports are initially compiled by local NWS offices before being reviewed by the National Centers for Environmental Information (Verbout et al. 2006) and entering the database. Fatality locations are obtained, if available, from the Storm Events Database, which includes records of the official NWS *Storm Data*. These locations range from permanent and mobile/trailer home to business and other/unknown (Table 1). The use of an "other/unknown" location within the *Storm Data* entry is reserved for direct fatalities—those directly attributable to the tornado—that occurred at a site not currently tabulated or that occurred at an unknown initial location (National Weather Service 2021). For this work, tornado fatality locations are grouped into nine categories: permanent home, mobile/trailer home, business, church, school, permanent structure, outside (outside/open areas and camping), vehicle, and other/unknown.

Population and housing information at the Census tract level are obtained from the United States Census Bureau and the

TABLE 2. Estimates of total population and total housing units by fatality location. Housing units are estimated as permanent and mobile-home units, respectively.

Fatality location	No. of tornadoes	No. of fatalities	Total population	Total housing units
Permanent home	495	636	502 771	113 076
Mobile home	495	671	50 987	22 168

American Community Survey (ACS) (https://www.census.gov/programs-surveys/acs), and the boundary shapefiles are obtained from the Topologically Integrated Geographic Encoding and Referencing (TIGER) database. Here, data from the 1990 and 2000 U.S. census, as well as the 2010 ACS 5-yr estimates, are included. Because detailed mobile-home residential population and vehicle information is not readily available from the decennial census or ACS, total mobile-home population is estimated through the product of the number of mobile homes and the average family size within mobile homes using information from the 2010 ACS 5-yr estimates. The average family size within mobile homes is calculated as 2.3, which is the quotient of the estimated U.S. mobile-home population (20 million) and the estimated number of mobile homes within the United States (8.6 million). Similarly, vehicle information is estimated at the per-capita and household level using total vehicle registrations. The number of vehicles per capita is calculated as 0.83, which is the quotient of the number of current vehicle registrations (273 million) and the U.S. population, and the number of vehicles per household is calculated as 1.9.

Estimates of total population and housing units are computed for each tornado using the method outlined in Fricker (2020b). Having estimates of total exposed population—the number of people within the damage path—and total exposed housing units—the number of housing units within the damage path—along with information on tornado fatalities, location, date, and time allows for the subsetting of tornadoes by their characteristics. For example, when subset by residential location (i.e., mobile and permanent home), it is possible to use the number of tornadoes, the number of fatalities, in conjunction with total exposed population and total exposed housing units to estimate fatality rates at the per-capita and per–housing unit level (Table 2).

The mapping of fatalities is performed using the dasymetric procedure outlined in Fricker et al. (2017b), which spatially distributes the number of fatalities from a tornado within and along the damage path. For this work, the resolution is set to a 0.6° (~60 km) raster grid (41 north–south cells and 96 east–west cells for a total of 3936 cells), so as to be consistent with previous work identifying tornado fatality locations (Ashley 2007). At a resolution of 0.6°, the cells are large enough to contain a sufficient number of killer tornado paths and small enough to capture local patterns in fatalities.

3. Results

a. *Tornado fatalities and fatality rates by year, month, and hour*

There were 495 killer tornadoes producing 1775 tornado fatalities over the 24-yr period 1995–2018. This corresponds to an average of 74 deaths in tornadoes each year. Tendencies in the annual number of tornado fatalities and killer tornadoes are consistent with steady numbers from 1995 to 2010 and decreased numbers thereafter (Fig. 1). By month, tornado fatalities occur overwhelmingly in April and May, followed by February and March. April and May account for 60% of all tornado fatalities over the time period. More than three-fourths (80%) of all killer tornadoes result in three or fewer deaths, with the 2011 Joplin tornado serving as the extreme outlier with 158 fatalities. The per-capita fatality rate—the number of tornado fatalities per person—in killer tornadoes over the time period is 0.32%, while the per–housing unit fatality rate—the number of tornado fatalities per housing unit—is 0.75% (Table 3). This means that, over the period, if a killer tornado impacted—or exposed—1000 people, we would expect 3 fatalities, and if a killer tornado impacted—or exposed—1000 housing units, we would expect 8 fatalities.

Because of the quality of the historical tornado record, these fatality rates can be broken down into annual, monthly, or hourly per-capita and per–housing unit rates. The highest annual per-capita fatality rate of the period is 3.9% in 2016, while the lowest annual per-capita fatality rate of the period is 0.06% in 2018. Interestingly, the active 2011 tornado year was in the bottom half of all annual per-capita fatality rates at 0.31%, although it is likely that this rate—which is nearly the 24-yr per-capita fatality rate—is lower because of the larger number of people impacted by killer tornadoes during 2011 relative to other years. The highest monthly per-capita fatality rate of the period is 0.80% in July, while the lowest monthly per-capita fatality rate is 0.12% in both September and October (Fig. 2). Similar to annual per-capita fatality rates, it is not the most active months of the year that have the highest per-capita fatality rates. In fact, cold-season tornadoes—here defined as the months of December, January, and February—have the highest per-capita fatality rates of any season (Table 3). The highest hourly per-capita fatality rate is 2% between 0500 and 0559 central standard time (CST), and the lowest hourly per-capita fatality rate is 0.04% between 1100 and 1159 CST (Fig. 2). When subset by day (0600–1759 CST), evening (1800–2359 CST), and night (0000–0559 CST), per-capita fatality rates at night were 2 times as high as during the evening and 3 times as high as during the day (Table 3).

The highest annual per–housing unit fatality rate of the period is 8.8% in 2016 and the lowest annual per–housing unit fatality rate of the period is 0.13% in 2018. These two years—2016 and 2018—stand out as the highest and lowest annual fatality rates, regardless of unit, over the period. At the monthly level, the highest per–housing unit fatality rate of the period is February at 1.6% and the lowest per–housing unit fatality rate of the period is September and October, both at

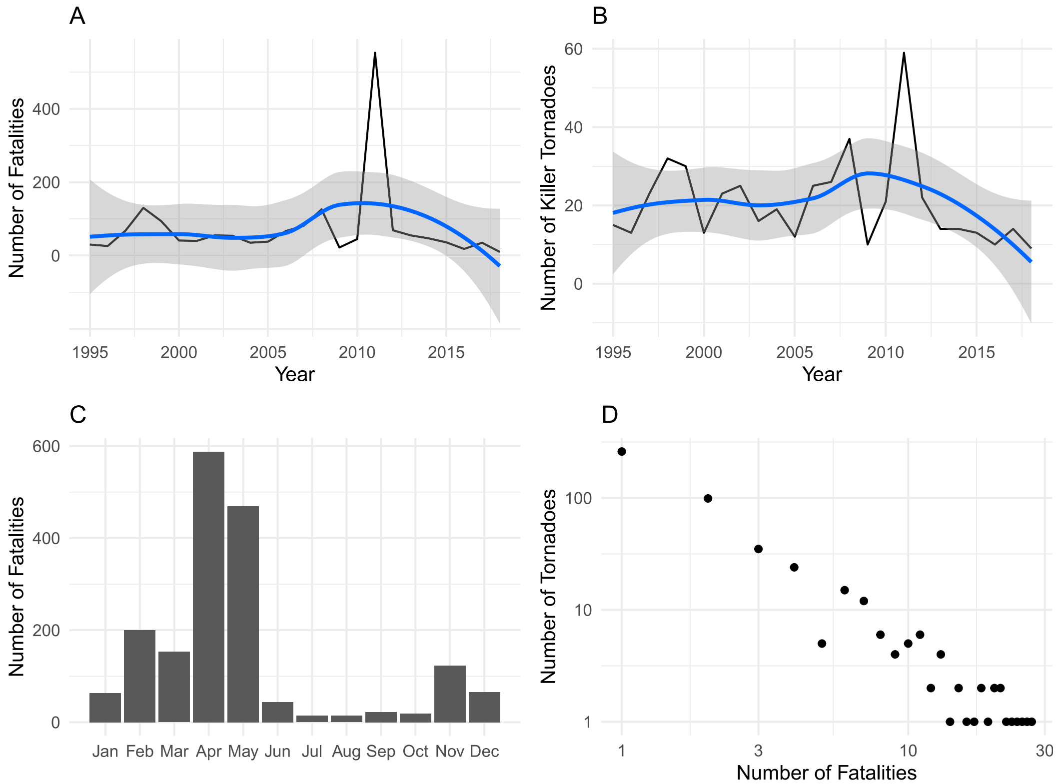

FIG. 1. Tornado fatalities: (a) time series of the number of tornado fatalities, (b) time series of the number of killer tornadoes, (c) monthly distribution of the number of tornado fatalities, and (d) cumulative distribution of tornado fatalities by number of tornadoes (log scale). In (a) and (b), the blue curve is a local regression and the gray band is the 95% uncertainty band on the curve.

0.30% (Fig. 2). By season, cold-season tornadoes again have the highest per–housing unit fatality rate at 1.1%. The highest hourly per–housing unit fatality rate is 4.9% between 0500 and 0559 CST, and the lowest hourly per–housing unit fatality rate is 0.11% between 1100 and 1159 CST (Fig. 2). When subset by day, evening, and night, per–housing unit fatality rates at night were again 2 times as high as during the evening and 4 times as high as during the day (Table 3).

b. Tornado fatalities and fatality rates by location

Tornado fatalities occur most often in residential structures. When subset by fatality location, as recorded in the NWS *Storm Data*, mobile homes account for the highest number of fatalities with 672, followed closely by permanent homes with 636 (Fig. 3). Thus, residential structures account for 74% of all tornado fatalities over the study period, with mobile homes accounting for 38% of all tornado fatalities, alone. Over the same time period, there were 141 vehicle fatalities, 77 outside fatalities, 76 permanent structure fatalities, 37 business fatalities, 19 church fatalities, 16 school fatalities, and 101 other/unknown fatalities (Fig. 3). Vehicle-related fatalities represent the largest category outside of residential structures, accounting for 8% of all tornado fatalities occurring over the period 1995–2018.

Patterns of fatalities by location over time are difficult to establish, in part, because of the annual volatility of tornado occurrence and differences in the daily patterns of people. Early in the period, mobile homes dominated the number of fatalities by location, while later in the period permanent homes are responsible for, on average, more fatalities than any other location (Fig. 3). All other fatality locations make up a small percentage (26%) of all fatalities throughout the period, however, the relationship between residential—permanent and mobile home—and nonresidential—all other locations—fatalities appears to be changing over the past decade, with residential fatalities decreasing and nonresidential fatalities staying constant. The seemingly unchanging numbers of nonresidential fatalities over the past decade are primarily driven by permanent structure and vehicle locations.

Fatality rates of locations with the largest numbers—permanent home, mobile home, and vehicle—are further examined to provide a quantification of risk and survivability among tornado shelter locations (Table 3). These rates suggest that an individual is 10 times as likely to die in a mobile home as in a permanent home. These rates also suggest that an individual is over 40 times as likely to die in a mobile home as in a vehicle and over 4 times as likely to die in a permanent home as in a vehicle. Making sense of the vehicle per-capita fatality rate here is difficult, because individuals are instructed to shelter in homes rather than in vehicles. This drives down the number of instances in which people are impacted by tornadoes while sheltering in a vehicle and thus makes the fatality rate much smaller than it otherwise would be.

At the housing unit level, fatality rates suggest that sheltering in a mobile home is also 10 times as likely to result in death as sheltering in a permanent home. Again, here the relationship between sheltering in a residential structure and a vehicle is difficult to tease out due to differences in circumstances leading to the sheltering of individuals in vehicles. Because individuals are instructed to shelter in homes rather than in vehicles, comparing object-level fatality rates (i.e., housing unit and vehicle) makes little sense. This comparison would result in a conclusion suggesting that vehicles are safer than mobile and permanent homes. At the very least, it is obvious that people are safer from the damaging effects of tornadoes in permanent homes than in vehicles.

A comparison of mobile-home and permanent-home fatalities and fatality rates uncovers patterns of destruction and highlights a number of physical and social systems at work. At both the per-capita and per–housing unit level, an individual is 10 times as likely to die in a mobile home as in a permanent home. Put another way, the survivability of an individual in a permanent home is estimated at 99.9% at the per-capita level and 99.7% at the per–housing unit level, whereas the survivability of an individual in a mobile home is estimated at 98.7% at the per-capita level and 97% at the per–housing unit level. The number of mobile-home fatalities, on average, over time is slightly decreasing, and the number of permanent-home fatalities over the same period is slightly increasing (Fig. 4). Seasonally, mobile-home fatalities occur in greater numbers during the cold season of November–February and permanent-home fatalities occur in greater numbers during the late-spring and early-summer months (April–July) (Fig. 4).

Reasons for slight changes in the annual number of mobile-home and permanent-home fatalities might include luck—powerful tornadoes not impacting a large number of mobile homes since 2011—an increased awareness of mobile-home vulnerabilities, and increased spending on mobile-home vulnerability research. Reasons for the seasonal difference in mobile-home and permanent-home fatalities likely include the spatial footprint and built environment, or the physical landscape of human settlement, of cold-season tornadoes in the Southeast and the spatial footprint and built environment of late-spring and early-summer tornadoes in the Great Plains, as well as natural variability in the location of tornadoes.

c. *Tornado fatalities and fatality rates by age and sex*

Older adults account for the highest number of tornado fatalities. When subset by age groups—under 18, 18–44, 45–64, and over 65—553 people between the ages of 45 and 64 were killed in tornadoes over the period, followed by 499 people over the age of 65, 438 people between the ages of 18 and 44, and 213 people under the age of 18; 31% of all tornado fatalities over the period were people between the ages of 45 and 64, whereas 28%, 25%, and 12% of all tornado fatalities over the period were people over the age of 65, people between the ages of 18 and 44, and people under the age of 18, respectively.

To understand whether these totals or percentages are disproportionate—signaling a potential vulnerability—the number or proportion of fatalities is compared with the number or proportion of population. One tendency that stands out when doing this is that older individuals—and not just the oldest individuals—are far more susceptible to being tornado fatalities than total numbers or percentages would suggest. People between the ages of 45 and 64 made up the largest total number of fatalities (553), and yet they are only the third-largest age group by total impacted population (~137 000). Similarly, people over the age of 65 made up the second-largest total number of fatalities (499) while being part of the smallest age group by total impacted population (~69 000) (Fig. 5). By percentage of fatalities and population, it is clear that the very young and very old have the most disproportionate relationship. People under the age of 18 represent 12% of all tornado fatalities but 25% of all people within the path of killer tornadoes, whereas people over the age of 65 represent 28% of all tornado fatalities but only 12% of all people within the path of killer tornadoes (Fig. 5).

TABLE 3. Fatality rates by study period, time of day, season, fatality location, age, and sex.

	Per-capita fatality rate	Per–housing unit fatality rate
Study period		
1995–2018	0.32%	0.75%
Time of day		
Day (0600–1759 CST)	0.28%	0.60%
Evening (1800–2359 CST)	0.50%	1.2%
Night (0000–0559 CST)	1%	2.4%
Season		
Dec–Feb	0.46%	1.1%
Mar–May	0.30%	0.70%
Jun–Aug	0.25%	0.57%
Sep–Nov	0.31%	0.76%
Fatality location		
Permanent home	0.13%	0.30%
Mobile home	1.3%	3%
Vehicle	0.03%	0.03%
Age		
Under 18	0.15%	0.09%
18–44	0.21%	0.19%
45–64	0.41%	0.23%
Over 65	0.72%	0.21%
Sex		
Male	0.32%	0.36%
Female	0.31%	0.37%

Fatality rates by age group further highlight differences in vulnerable populations (Table 3). At the per-capita level, an individual over the age of 65 is nearly 5 times as likely to die in a tornado as an individual who is under the age of 18. Similarly, an individual between the ages 45 and 64 is 2 times as likely to die in a tornado as an individual who is between the ages of 18 and 44. Fatality rates at the housing unit level are more difficult to establish for age groups, in part, due to the limitations in the quality of the data. That is, because no available dataset provides the age groups of the owners or dwellers of a housing unit, all age groups must be evaluated on the same total housing units.

Women account for more fatalities than men over the study period: 875 women were killed in tornadoes, making up 51% of

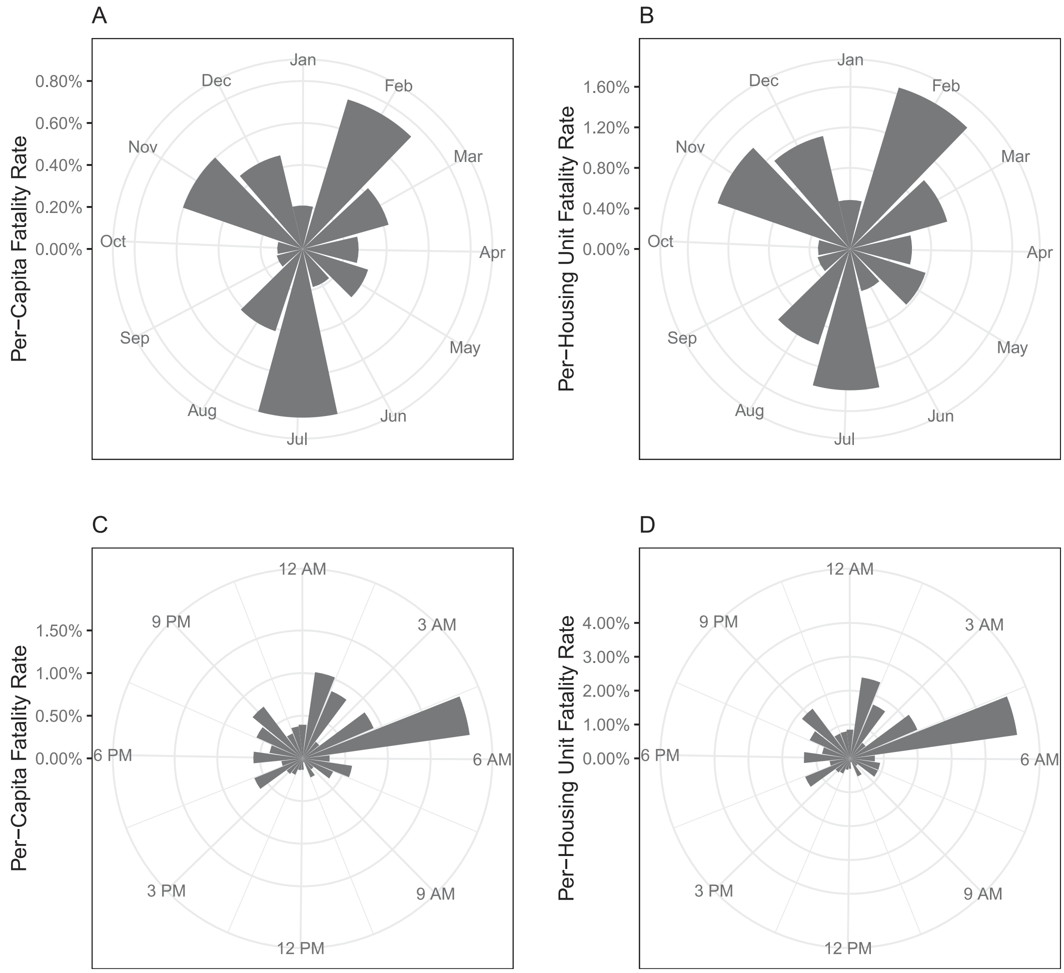

FIG. 2. Fatality rates by month and hour: (a) per-capita fatality rate by month, (b) per–housing unit fatality rate by month, (c) per-capita fatality rate by hour, and (d) per–housing unit fatality rate by hour.

assigned fatalities by sex, while 856 men were killed in tornadoes, making up the remaining 49% of assigned fatalities by sex. Perhaps unsurprisingly, the impacted total population by sex mirrors the proportion of fatalities, with 51% of the impacted population (~283 000) being women and 49% of the impacted population being men (~271 000). Because total fatalities and total population by sex are similar in proportion, so too are the per-capita and per–housing unit fatality rates by sex (Table 3).

d. *A geographic distribution of tornado fatalities*

Visualizing tornado fatalities spatially across a range of climatological and structural categories can provide further insight into geographic patterns of fatalities. At the seasonal level, it is clear that tornado fatalities follow storm activity throughout the year. During the cold season, the majority of tornadoes occur in the mid-South—the area consisting of western Tennessee, northern Mississippi, southern Missouri, western Kentucky, northeast and northwest Arkansas, and northern Alabama (Fig. 6). During the most active season of the year—March, April, and May—tornado fatalities are spread throughout the southern Great Plains, Midwest, and Southeast (Fig. 6). Tornado fatalities begin to migrate into the northern Great Plains, upper Midwest, and Northeast during June, July, and August (Fig. 6), occurring far less frequently before once again concentrating in the mid-South and Southeast during September, October, and November (Fig. 6).

The geographic distribution of tornado fatalities by time of day reveals an obvious concentration of total fatalities across the mid-South and Southeast. During the day (0600–1759 CST), tornado fatalities occur most often across urban centers of the southern Great Plains, and the mid-South—particularly a swath from central Arkansas through northern Mississippi and Alabama into southern Tennessee (Fig. 7). During the evening and night hours (1800–0559), tornado fatalities are again concentrated across the mid-South but appear to extend farther south into the coastal areas of the Southeast and Florida (Fig. 7).

Mapping all tornado fatalities and killer tornadoes indicates that the highest risk associated with tornadoes is found across the mid-South. A large swath of high numbers of tornado fatalities and killer tornadoes is seen across central and northern Mississippi and Alabama and extending from central Arkansas through south-central Tennessee (Fig. 8). When subset by residential structure—permanent homes and

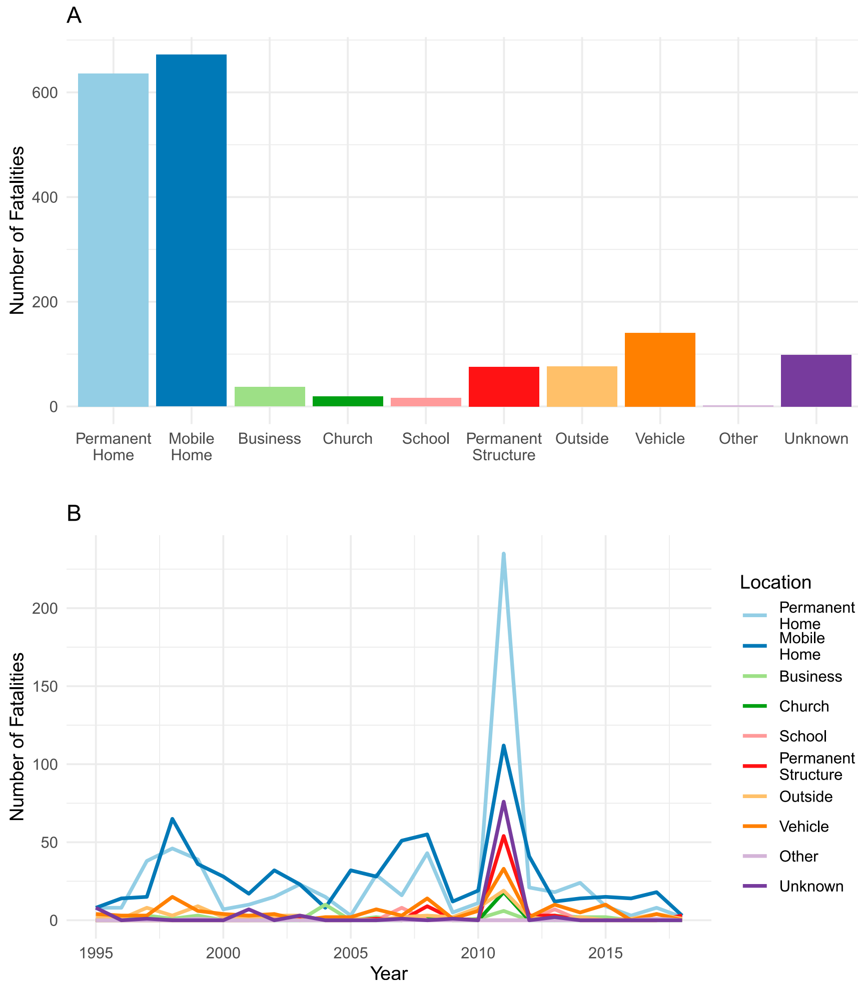

FIG. 3. Tornado fatalities by location: (a) number of tornado fatalities by location and (b) number of tornado fatalities by location and year.

mobile homes—it is clear that the average spatial distribution of mobile-home fatalities is wider than that of permanent-home fatalities, which underscores the high vulnerability of those structures to tornadoes and the distribution of housing stock across the country. Mobile-home fatalities occur throughout much of the southern Great Plains, mid-South, and Southeast, whereas permanent-home fatalities occur throughout much of the southern Great Plains, Midwest, and mid-South (Fig. 8).

4. Discussion

Fatalities are the ultimate loss associated with any tornado. Understanding the relationship between risk factors and tornado fatalities has been a long standing goal of previous literature. While we have made substantial gains in making sense of physical, socioeconomic, and demographic factors that increase the number of tornado fatalities, we have not extensively analyzed the differences in tornado fatality rates across physical and social categories. Here, rates across physical and social factors—fatality location, demographic profiles, and year, month, and hour of occurrence—are estimated to gain a deeper understanding of tornado survivability.

There were 495 killer tornadoes over the period 1995–2018 that produced 1775 fatalities, corresponding to an average of 74 deaths each year. Tendencies in the annual number of tornado fatalities and killer tornadoes are steady from 1995 to 2010, decreasing thereafter. In the short term, this suggests that as a community we are making progress in the tornado fatality problem. However, in the long term, even an average death rate of 74 people per year is an increase from the mid-1970s through the mid-1990s (Fricker et al. 2017b). By month, April and May dominate the number of tornado fatalities over the period, consistent with previous research that evaluates tornado fatalities over much larger study periods (Ashley 2007; Fricker et al. 2017b). This suggests that even in the face of a recently reduced average annual fatality count—relative to the early period of record (1995–2010) in this study—seasonal rates of tornado fatalities remain stable.

The 24-yr per-capita fatality rate is 0.32%, and the per–housing unit fatality rate is 0.75%. Perhaps unsurprisingly,

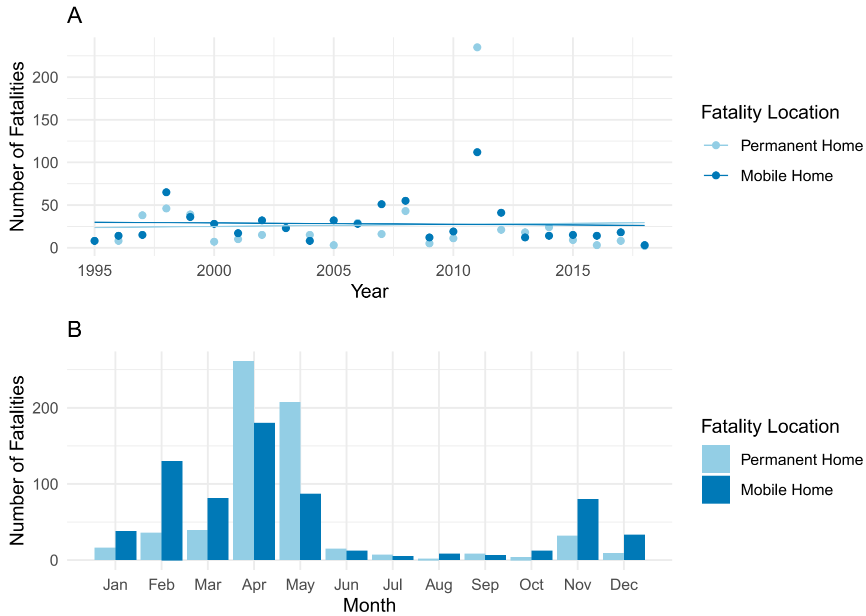

FIG. 4. Permanent-home and mobile-home tornado fatalities: (a) annual number of tornado fatalities by location and (b) monthly number of tornado fatalities by location. The blue curves are local regressions.

these rates are slightly lower than those generally found in the most high-impact tornadoes of the past few decades (Biddle 2007; Kuligowski et al. 2014). When considering only killer tornadoes, the fatality rate is higher at both the per-capita and per–housing unit level relative to casualty-producing tornadoes (Fricker 2020a). This is likely due to a combination of smaller numbers and more intense tornadoes (i.e., killer tornadoes are, on average, more powerful

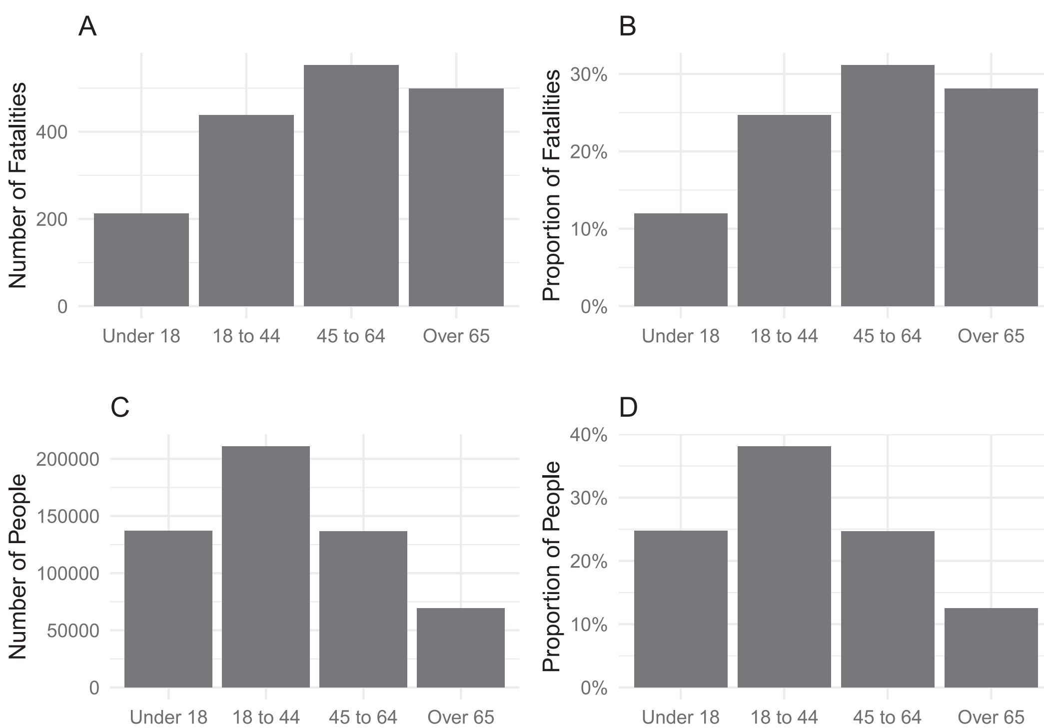

FIG. 5. Tornado fatalities by age: (a) number of tornado fatalities by age, (b) proportion of tornado fatalities by age, (c) number of people impacted by killer tornadoes by age, and (d) proportion of people impacted by killer tornadoes by age.

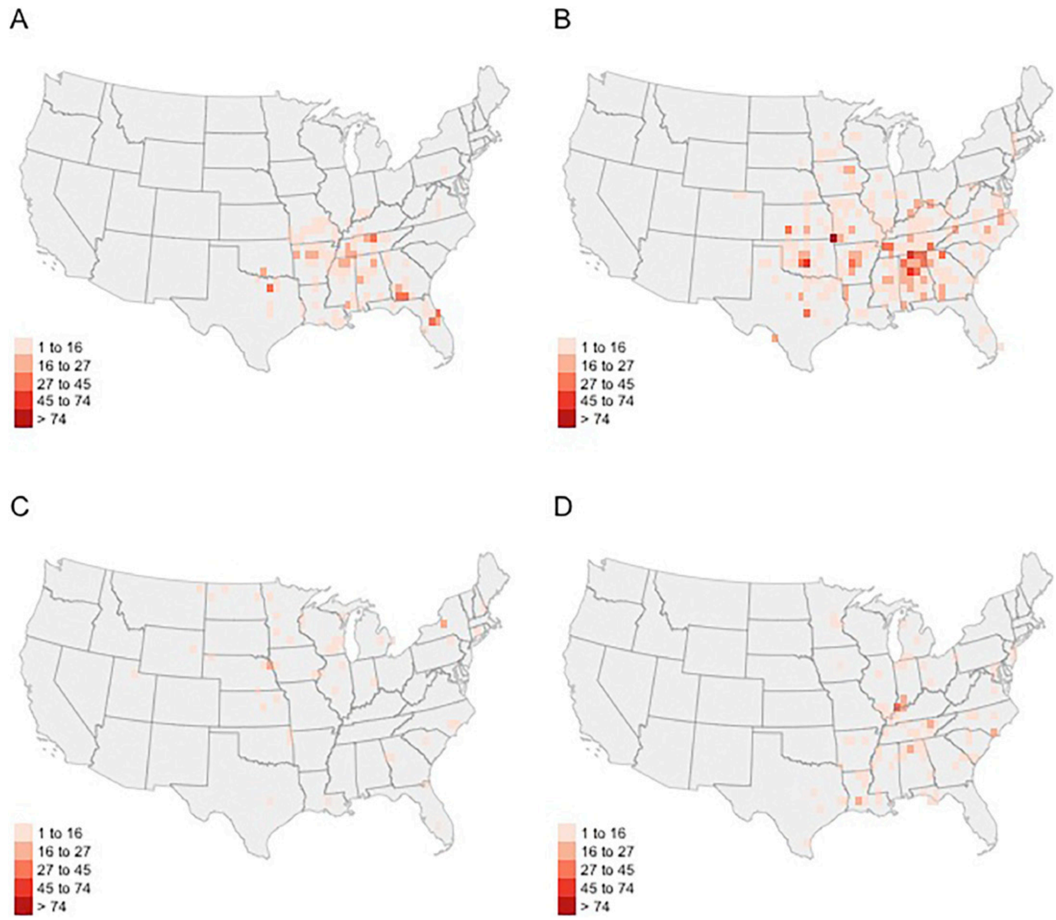

FIG. 6. Spatial distribution of tornado fatalities by season: (a) tornado fatalities in December, January, and February, (b) tornado fatalities in March, April, and May, (c) tornado fatalities in June, July, and August, and (d) tornado fatalities in September, October, and November.

than casualty-producing tornadoes). Annual tornado per-capita fatality rates range from a high of 3.9% in 2016 to a low of 0.06% in 2018, while annual tornado per–housing unit fatality rates range from a high of 8.8% in 2016 to a low of 0.13% in 2018. Differences in the annual fatality rates might be the result of the interaction between the number of killer tornadoes, the average intensity of the killer tornadoes, and the location in which these storms exist. For example, the low fatality rates in 2018 can be explained by a relatively nonactive season—9 killer tornadoes—in combination with a low-intensity season—average killer tornado EF rating of 1.4. Given that tornadoes may be becoming increasingly powerful (Elsner et al. 2019), it is somewhat surprising to see a recent season as the least deadly, although the result stands to further support increasing year-to-year changes (volatility) in tornado activity (Tippett et al. 2015).

Seasonal and diurnal per-capita and per–housing unit fatality rates align with our current understanding of human vulnerability to the tornado hazard. Cold-season tornadoes—December, January, and February—have the highest fatality rates of any season. Reasons for this may be the result of meteorological and climatological conditions—faster forward speeds, faster tropospheric flow, and so on—that make forecasting difficult (Childs et al. 2018), as well as the location of typical cold-season tornado activity—mid-South and Southeast—which corresponds to higher built and social vulnerabilities. Tornadoes occurring at night (0000–0559 CST) are 2 times as deadly as tornadoes during the evening (1800–2359 CST), and 3–4 times as deadly as tornadoes during the day (0600–1759 CST). This disparity is almost certainly the result of a combination of factors, including difficulty in visually identifying a tornado on the ground, difficulty in warning individuals of a possible tornado, and the daily patterns of people (i.e., most people are asleep during the night). And while the heightened risk of tornado fatalities at night is well known (Ashley et al. 2008), quantifying this risk as a fatality rate—beyond total fatalities or a proportion of killer tornadoes and all tornadoes—can provide further evidence to investigate the relationship between tornado warning dissemination, nocturnal forecasting challenges, and public risk perception (Mason et al. 2018; Ellis et al. 2020; Krocak et al. 2021).

Residential structures account for 74% of all tornado fatalities over the study period, with mobile homes accounting for 38% of all tornado fatalities alone. When broken

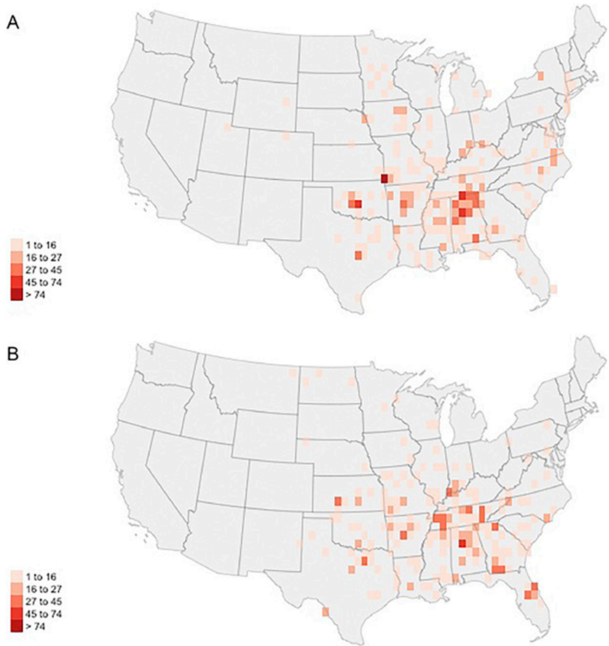

FIG. 7. Spatial distribution of tornado fatalities by time of day: (a) tornado fatalities during the daytime hours (0600–1759 CST) and (b) tornado fatalities during the evening and night hours (1800–0559 CST).

down by residential structure—permanent home and mobile home—per-capita and per–housing unit fatality rates are over 10 times as high for people sheltering in mobile homes as for people sheltering in permanent homes. This result is identical to the findings of Sutter and Simmons (2010), despite having different definitions of fatality rates, and though the risk and vulnerability of mobile-home residents to the tornado hazard are well established (Boruff et al. 2003; Ashley 2007; Strader and Ashley 2018; Ash et al. 2020), efforts must continue to be made to close the gap between residential structures if the ultimate goal of the community is to reduce the loss of life from tornadoes. That said, these efforts cannot be made despite or in place of research that focuses on all tornado fatality locations. By placing less emphasis (i.e., research funding) on nonresidential tornado fatalities—business, church, school, outside, and so on—it becomes likely that the relationship between residential and nonresidential fatalities will continue to evolve, resulting in nonresidential fatalities accounting for a higher proportion of all tornado fatalities in the future (Fig. 9).

The mapping of tornado fatalities throughout a range of factors reveals consistent patterns across space. Unsurprisingly, the mid-South and Southeast have produced the highest numbers of tornado fatalities over the study period, in part, due to the complex blending of physical, social, and economic vulnerabilities. And while the mid-South and Southeast have long been a region of concern for tornado fatalities (Ashley 2007; Fricker et al. 2017b; Agee and Taylor 2019), it appears that the spatial distribution of tornado fatalities in the United States is becoming more concentrated over time. For example, Ashley (2007) finds that the number of tornado fatalities and killer tornadoes is highest in the interior South (i.e., mid-South) from 1985 to 2005 with small groups of high fatality numbers in the central Great Plains and Midwest. Here, the vast majority of all tornado fatalities over the period 1995–2018, have occurred in the mid-South and Southeast with low geographic dispersion in other regions of the country. Nowhere is this pattern more noticeable than in the location of permanent-home fatalities, where a large swath of high numbers exists across the Tennessee Valley, in contrast to earlier work (Ashley 2007). Whether this concentration of tornado fatalities across the mid-South and Southeast signals a shift in the spatial dimensions of human vulnerability to tornadoes likely depends on the framing of physical and social systems and an understanding of short- and long-term climatological trends (Moore 2017; Gensini and Brooks 2018; Elsner et al. 2019).

Application of these fatality rates can result in simpler and more straight-forward predictions of tornado impacts at the community level. For example, given the size of any community, it is possible to use the 24-yr per-capita or per–housing unit fatality rate as a multiplier to estimate the number of fatalities expected in any one tornado. Further, should a community exist in an area impacted by cold-season tornadoes (e.g., mid-South and Southeast) or be home to vulnerable populations (e.g., older adults), the seasonal or age fatality rate could be used as a multiplier to estimate the number of fatalities in—what are likely—higher-risk tornadoes. Given the length of the SPC historical database, it is also possible to compare annual tornado climatologies with current-year activity as a means to select an annual fatality rate—between 1995 and 2018—as a multiplier to estimate the number of fatalities that might exist in any given community.

Selection of which fatality rate to use (i.e., per capita or per housing unit) is dependent on the size of a community and the quality of demographic or building data available. Communities home to a large number of people might be better suited to use per-capita fatality rates, while communities of densely populated neighborhoods might be better suited to use per–housing unit fatality rates. Ultimately, these rates should allow emergency managers, meteorologists, and planners to attack questions related to what might happen in a tornado event better than the most extreme events. That said, high-impact tornadoes play a significant role in the overall fatality rates found in this work. Removing the 2011 Joplin tornado from the analysis drops the per-capita fatality rate to 0.29% and the per–housing unit fatality rate to 0.68%. It also results in a shift in the relationship between permanent-home fatalities and mobile-home fatalities to mobile homes having a slightly higher average number of fatalities per year than permanent homes.

5. Conclusions

The United States experiences more tornadoes, on average, than any other country on Earth. As a result, the United States also experiences more tornado fatalities, on average, than any other country on Earth. While previous work on tornado fatalities has largely focused on the number and location of deaths, here, tornado fatalities over the period 1995–2018 are

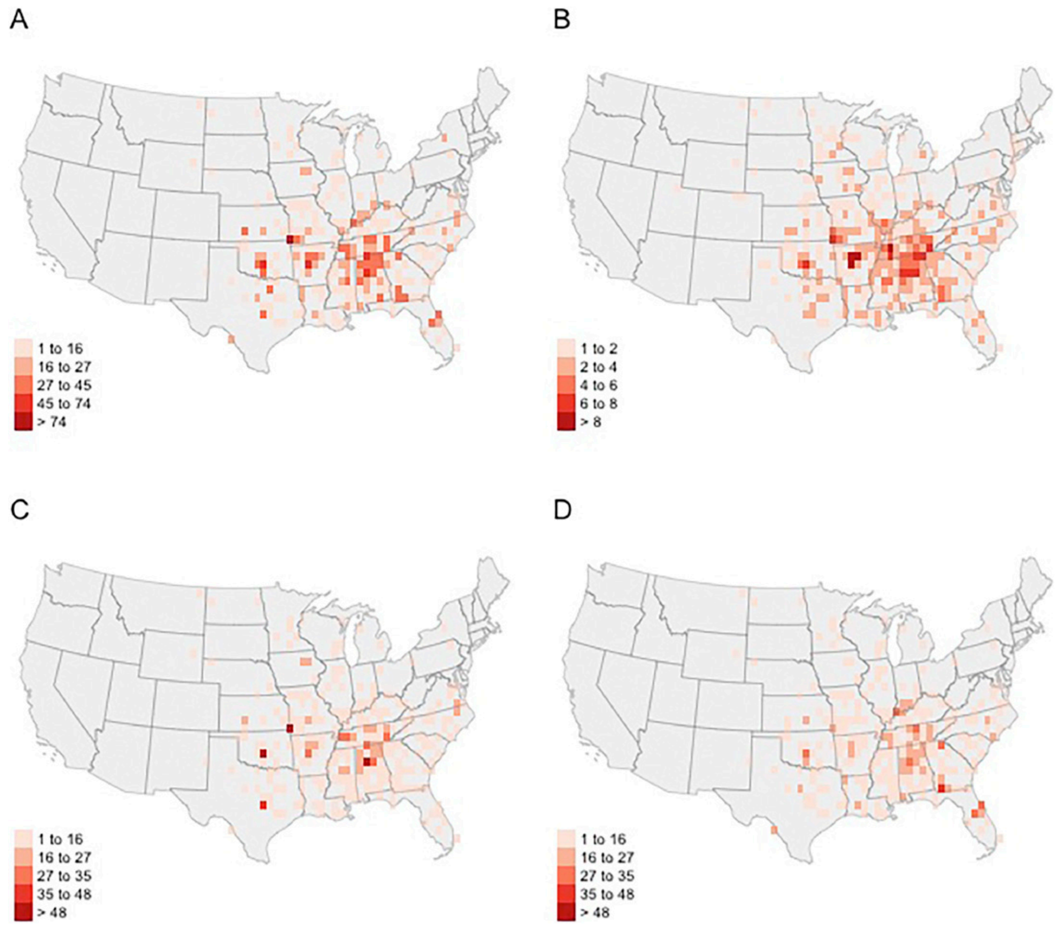

FIG. 8. Spatial distribution of tornado fatalities: (a) total fatalities, (b) killer tornadoes, (c) permanent-home fatalities, and (d) mobile-home fatalities.

placed in the context of rates—the number of fatalities per person or per housing unit—and evaluated through multiple physical and social factors to provide a more complete quantitative foundation of tornado fatalities.

A common theme that stands out when comparing fatality rates across different factors is the high survivability of individuals in killer tornadoes. Even in highly vulnerable structures (i.e., mobile homes), the survivability of an individual is 97% or higher. While reducing the number of people killed in tornadoes is a worthy endeavor, the weather community—including NWS meteorologists, emergency managers, and hazards scientists—has provided a strong base from which to work.

Patterns in fatality rates are consistent with prior research on the tornado fatality problem. For example, tornadoes at night are associated with much higher fatality rates than those during the day or evening. Mobile-home fatality rates are much higher than permanent-home fatality rates, and fatality rates of older individuals are disproportionately higher than for any other age group. The mapping of tornado fatality locations further indicates that the mid-South and Southeast United States are the regions responsible for the majority of tornado fatality rates and that mobile-home fatalities show greater spatial distribution than permanent-home fatalities.

The utility of these fatality rates is highly dependent on the user. Emergency managers, meteorologists, and planners might use the rates to better prepare for high-impact events, while researchers might use the rates to ground future projects. For example, the mapping of fatality locations suggests an increased concentration of tornado fatalities across the mid-South and Southeast over the past two decades. Future research could leverage the location of tornado fatalities to quantify the impact migration patterns, aging infrastructure, and/or political ecology (e.g., redlining) have on the number or rate of fatalities and whether or not these social factors are as important as physical factors (e.g., increasingly powerful tornadoes) in explaining the tornado fatality landscape.

Moving forward, it is important to continue to build a body of tornado fatality literature with a foundation in both the physical and social sciences. Quantitative evidence, such as this work, is only one side of the solution. Qualitative and mixed-methods evidence is the other. If the goal is to reduce the loss of life and property to tornadoes, then we must continue to combine physical and social science perspectives to tease out

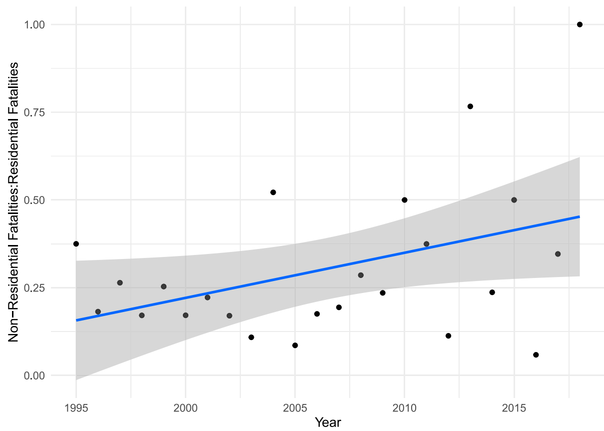

FIG. 9. Proportion of tornado fatalities occurring in nonresidential structures relative to residential structures. The blue line curve is a local regression, and the gray band is the 95% uncertainty band on the curve.

relationships between tornado fatality rates and locations, changing tornado behavior, and changing social systems.

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