1 **Tornado fatalities in context: 1995–2018**

2 Tyler Fricker*

3 *University of Louisiana Monroe, Monroe, Louisiana*

4 Corey Friesenhahn

5 *Texas A&M University, College Station, Texas*

6 **Corresponding author address:* Tyler Fricker, School of Sciences, University of Louisiana Mon-
7 roe, Monroe, Louisiana

8 E-mail: tfricker@ulm.edu

ABSTRACT

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

20 **Significance Statement**

21 Tornadoes are among the deadliest natural hazards on Earth. Nowhere is the impact of tornadoes
22 felt more than in the United States, where around 70 people, on average, are killed each year.
23 While previous work has focused on the number or location of tornado fatalities, here fatalities are
24 evaluated through rates at both the population and household level across a number of physical and
25 social factors. Fatality rates are highest during the cold season, at night, and for mobile homes and
26 older adults. Across space, fatalities appear to be increasingly concentrated throughout the Mid-
27 South and Southeast relative to previous studies. These results can be used to better prepare for
28 tornado fatality events or to provide further quantitative evidence to ground future tornado fatality
29 research.

30 **1. Introduction**

31 Tornadoes have killed around 70 people, on average, per year in the United States over the past
32 30 years. In fact, tornadoes account for the third highest average annual weather-related fatality
33 rate in the country, trailing only extreme heat and floods. Even in years with below average
34 numbers of killer tornadoes, the loss of life can devastate and impact communities throughout the
35 country. For example, 2018 was the least active killer tornado season over the past 24 years, yet,
36 ten people still lost their lives.

37 Some previous studies have focused on the number and location of tornado fatalities (Grazulis
38 1990; Hammer and Schmidlin 2000; Ashley 2007; Fricker et al. 2017b; Paulikas and Schmidlin
39 2017; Agee and Taylor 2019). For example, Grazulis (1990) provides a historical narrative of sig-
40 nificant and killer tornado reports since the late nineteenth century, while Hammer and Schmidlin
41 (2000) and Paulikas and Schmidlin (2017) detail vehicle-related tornado fatalities over the periods
42 1900–1998, and 1991–2015, respectively. Ashley (2007) examines spatial and temporal aspects

43 of all tornado fatalities between 1880–2005, while Fricker et al. (2017b) use a dasymetric method
44 to map all tornado fatalities across the most tornado-prone region of the United States over the
45 period 1955–2016. More recently, Agee and Taylor (2019) identify which states have been the
46 most impacted by tornado fatalities dating back to 1808 using a death per population index. Con-
47 sistency in the results of these works can be seen in the spatial extent of tornado fatalities, which
48 have occurred in the largest numbers in the Mid-South and Southeast United States, most notably
49 in the states of Alabama, Arkansas, and Mississippi.

50 Other studies have focused on the identification of risk factors associated with tornado fatalities
51 (Kilijanek and Drabek 1979; Simmons and Sutter 2005, 2008, 2009; Donner 2007; Ashley et al.
52 2008; Dixon and Moore 2012; Donner et al. 2012; Ashley et al. 2014; Lim et al. 2017; Fricker et al.
53 2017a; Elsner et al. 2018a; Masoomi and van de Lindt 2018; Fricker and Elsner 2019; Strader et al.
54 2021). For example, Simmons and Sutter (2005, 2008, 2009), Lim et al. (2017), and Masoomi and
55 van de Lindt (2018) use regression models to explain the impact different physical, socioeco-
56 nomic, and demographic factors have on fatalities. Fricker et al. (2017a) and Elsner et al. (2018a)
57 use similar regression techniques to explain the relative impact wind energy—estimated energy
58 dissipation at the surface—and population density have on casualties—including fatalities—while
59 Fricker and Elsner (2019) evaluate the residuals of a regression model to identify communities that
60 are impacted by unusually devastating tornadoes. Kilijanek and Drabek (1979), Donner (2007),
61 Ashley et al. (2008, 2014), Dixon and Moore (2012), Donner et al. (2012), and Strader et al. (2021)
62 use other qualitative, geographic, and statistical methods to identify patterns between risk factors
63 and tornado fatalities. Results of these works show that the number of tornado fatalities increases
64 with tornado strength, population density, percentage of mobile homes, and the number of older
65 adults (age 65+) in an area. Additionally, results of these works show that nocturnal tornadoes—
66 those occurring between sunset and sunrise—are more than twice as likely to result in a tornado

67 fatality than tornadoes occurring during the day, and that Southeast National Weather Service
68 (NWS) county warning areas are the most prone to tornado fatalities due to the juxtaposition of
69 tornado risk and high social vulnerability.

70 Absent from these previous studies is a fine-scale understanding of the rate of tornado fatalities,
71 that is, the number of tornado fatalities per-capita or per-housing unit. To this point, most of our
72 knowledge related to fine-scale fatality rates comes from surveys of high-impact tornado events.
73 For example, Biddle (2007) examines the 1999 Oklahoma City, Oklahoma tornado that resulted in
74 36 fatalities and finds that $\sim 50,000$ people and 4,300 housing units were impacted by the tornado,
75 which corresponds to a per-capita fatality rate of .072% and a per-housing unit fatality rate of .84%.
76 Similarly, Kuligowski et al. (2013) investigate the 2011 Joplin, Missouri tornado that resulted in
77 158 fatalities and find that an estimated 20,820 people and 7,500 housing units were impacted
78 by the tornado, corresponding to a per-capita fatality rate of .76% and a per-housing unit fatality
79 rate of 2.1%. More recently, Fricker (2020a) uses tornado-level socioeconomic and demographic
80 estimates to investigate tornado casualty rates by exposed person and exposed housing unit in the
81 United States. Results show that in casualty-producing tornadoes—those that produce at least one
82 injury or death—over the period 1995–2016, the estimated per-capita fatality rate in the United
83 States is .15% and the estimated per-housing unit fatality rate in the United States is .36%. These
84 fatality rates, however, exist at a general level, which means that individual fatality rates at any
85 Fujita (F) or Enhanced Fujita (EF) Scale rating, for any fatality location (e.g. mobile or permanent
86 home), across any diurnal or seasonal scale remain unknown.

87 The usefulness of fatality rates in the prediction of tornado impacts can be linked to the simplic-
88 ity in which they exist. Knowing the rate at which people are killed in tornadoes at the per-capita
89 or per-housing unit level allows emergency managers, meteorologists, or planners to think about
90 worst-case or what-if scenarios (Clarke 2005; Wurman et al. 2007; Antonescu et al. 2018) in their

91 local communities. For example, using the fatality rates found in Fricker (2020a), if an emergency
92 manager works for a city of 50,000 people with 10,000 housing units and predicts the worst case
93 scenario for any individual tornado is the impact of half the population and a third of the housing
94 units, they would estimate, on average, that the tornado would result in 38 fatalities ($25,000 \times$
95 $.0015$) at the per-capita level or 12 fatalities ($3,333 \times .0036$) at the per-housing unit level. In ad-
96 dition, more detailed—or appropriate—fatality estimates could be made for communities through
97 an overlay analysis of historical tornado paths and current population or housing unit data. In
98 this sense, communities could plan and prepare for what fatality events might look like if similar
99 tornadoes were to impact the area again.

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

110 **2. Data and Methods**

111 Tornado reports for all killer tornadoes—tornadoes that cause at least one fatality—over the pe-
112 riod 1995–2018 are obtained from the U.S. Storm Prediction Center’s (SPC) historical database
113 (<https://www.spc.noaa.gov/gis/svrgis/>). These reports are initially compiled by local

114 NWS offices before being reviewed by the National Center for Environmental Information (Ver-
115 bout et al. 2006) and entering the database. Fatality locations are obtained, if available, from the
116 Storm Events Database, which includes records of the official NWS *Storm Data*. These locations
117 range from permanent and mobile/trailer home to business and other/unknown (Table 1). The
118 use of an other/unknown location within the *Storm Data* entry is reserved for direct fatalities—
119 those directly attributable to the tornado—that occurred at a site not currently tabulated or that
120 occurred at an unknown initial location (National Weather Service 2016). For this work, tornado
121 fatality locations were grouped into nine categories: permanent home, mobile/trailer home, busi-
122 ness, church, school, permanent structure, outside (outside/open areas and camping), vehicle, and
123 other/unknown.

124 Population and housing information at the Census tract level are obtained from the United
125 States Census Bureau and the American Community Survey (ACS) ([https://www.census.gov/](https://www.census.gov/programs-surveys/acs)
126 [programs-surveys/acs](https://www.census.gov/programs-surveys/acs)) and the boundary shapefiles are obtained from the topologically inte-
127 grated geographic encoding and referencing (TIGER) database. Here, data from the 1990 and
128 2000 Census, as well as the 2010 ACS five-year estimates, are included. Because detailed mobile
129 home residential population and vehicle information is not readily available from the decennial
130 Census or ACS, total mobile home population is estimated through the product of the number of
131 mobile homes and the average family size within mobile homes using information from the 2010
132 ACS 5-year estimates. The average family size within mobile homes is calculated as 2.3, which is
133 the quotient of the estimated United States mobile home population (20 million) and the estimated
134 number of mobile homes within the United States (8.6 million). Similarly, vehicle information
135 is estimated at the per-capita and household level using total vehicle registrations. The number
136 of vehicles per-capita is calculated as .83, which is the quotient of the number of current vehicle

137 registrations (273 million) and the U.S. population, and the number of vehicles per household is
138 calculated as 1.9.

139 Estimates of total population and housing units are computed for each tornado using the method
140 outlined in Fricker (2020b). Having estimates of total exposed population and total exposed hous-
141 ing units along with information on tornado fatalities, location, date, and time allows for the sub-
142 setting of tornadoes by their characteristics. For example, when subset by residential location
143 (i.e. mobile and permanent home), it is possible to use the number of tornadoes, the number of
144 fatalities, in conjunction with total exposed population and total exposed housing units to estimate
145 fatality rates at the per-capita and per-housing unit level (Table 2).

146 The mapping of fatalities is performed using the dasymetric procedure outlined in Fricker et al.
147 (2017b), which spatially distributes the number of fatalities from a tornado within and along the
148 damage path. For this work, the resolution is set to a 0.6° (~ 60 km) raster grid (41 north-south
149 cells and 96 east-west cells for a total of 3936 cells), so as to be consistent with previous work
150 identifying tornado fatality locations (Ashley 2007). At a resolution of 0.6° , the cells are large
151 enough to contain a sufficient number of killer tornado paths and small enough to capture local
152 patterns in fatalities.

153 **3. Results**

154 *a. Tornado Fatalities and Fatality Rates by Year, Month, and Hour*

155 There were 495 killer tornadoes producing 1775 tornado fatalities over the period 1995–2018.
156 This corresponds to an average of 74 deaths in tornadoes each year. Tendencies in the annual
157 number of tornado fatalities and killer tornadoes are consistent with steady numbers from 1995 to
158 2010 and decreased numbers thereafter (Fig. 1). By month, tornado fatalities occur overwhelm-

ingly 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, Missouri 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 .32%, while the per-housing unit fatality rate—the number of tornado fatalities per housing unit—is .75% (Table 3). This means that, over the period, if a killer tornado impacted 1000 people, we would expect 3 fatalities, and if a killer tornado impacted 1000 housing units we would expect 8 fatalities.

Owing to 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 .06% in 2018. Interestingly, the active 2011 tornado year was in the bottom half of all annual per-capita fatality rates at .31%, though it is likely that this rate—which is nearly the 24-year per-capita fatality rate—is lower due to 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 .80% in July, while the lowest monthly per-capita fatality rate is .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 5:00 a.m.–5:59 a.m. Central Standard Time (CST), while the lowest hourly per-capita fatality rate is .04% between 11:00 a.m.–11:59 a.m. CST (Fig. 2). When subset by day (6:00 a.m.–5:59 p.m. CST), evening (6:00 p.m.–11:59 p.m. CST), and night (12:00 a.m.–5:59 a.m. CST), per-capita fatality

rates at night were twice as high as during the evening and three 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 .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 .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 5:00 a.m.–5:59 a.m. CST, and the lowest hourly per-housing unit fatality rate is .11% between 11:00 a.m.–11:59 a.m. CST (Fig. 2). When subset by day, evening, and night, per-housing unit fatality rates at night were again twice as high as during the evening and four 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.

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

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

223 At the housing unit level, fatality rates suggest that sheltering in a mobile home is also ten times
224 more likely to result in death than sheltering in a permanent home. Again, here the relationship
225 between sheltering in a residential structure and a vehicle is difficult to tease out due to differ-
226 ences in circumstances leading to the sheltering of individuals in vehicles. Because individuals
227 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.

Comparing 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 ten times more likely to die in a mobile home than 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, while 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, while 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 of cold season tornadoes—in the Southeast—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.

249 *c. Tornado Fatalities and Fatality Rates by Age and Sex*

250 Older adults account for the highest number of tornado fatalities. When subset by age groups—
251 under 18, 18 to 44, 45 to 64, and over 65—553 people between the ages of 45 and 64 were killed in
252 tornadoes over the period, followed by 499 people over the age of 65, 438 people between the ages
253 of 18 and 44, and 213 people under the age of 18. By proportion, 31% of all tornado fatalities over
254 the period were people between the ages of 45 and 64, while 28%, 25%, and 12% of all tornado
255 fatalities over the period were people over the age of 65, people between the ages of 18 and 44,
256 and people under the age of 18, respectively.

257 To understand whether or not these totals or percentages are disproportionate—signaling a po-
258 tential vulnerability—the number or proportion of fatalities is compared to the number or propor-
259 tion of population. One tendency that stands out when doing this, is that older individuals—and
260 not just the oldest individuals—are far more susceptible to being tornado fatalities than total num-
261 bers or percentages would suggest. People between the ages of 45 and 64 made up the largest total
262 number of fatalities (553), yet are only the third largest age group by total population (~137,000).
263 Similarly, people over the age of 65 made up the second largest total number of fatalities (499),
264 while being part of the smallest age group by total population (~69,000) (Fig. 5). By percentage
265 of fatalities and population, it is clear that the very young and very old have the most dispropor-
266 tionate relationship. People under the age of 18 represent 12% of all tornado fatalities, but 25% of
267 all people within the path of killer tornadoes, while people over the age of 65 represent 28% of all
268 tornado fatalities, but only 12% of all people within the path of killer tornadoes (Fig. 5).

269 Fatality rates by age group further highlight differences in vulnerable populations (Table 3). At
270 the per-capita level, an individual over the age of 65 is five times more likely to die in a tornado
271 than an individual who is under the age of 18. Similarly, an individual between the ages 45 and

64 is twice as likely to die in a tornado than 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 data set 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 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 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, as well as northern Alabama (Fig. 6). During the most active season of the year—March, April, and May (MAM)—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).

295 The geographic distribution of tornado fatalities by time of day reveals an obvious concentration
296 of total fatalities across the Mid-South and Southeast. During the day (6:00 a.m.–5:59 p.m. CST),
297 tornado fatalities occur most often across urban centers of the Southern Great Plains, and the Mid-
298 South—particularly a swath from central Arkansas through northern Mississippi and Alabama into
299 southern Tennessee (Fig. 7). During the evening and night hours (6:00 p.m.–5:59 a.m.), tornado
300 fatalities are again concentrated across the Mid-South, but appear to extend further south into the
301 coastal areas of the Southeast and Florida (Fig. 7).

302 Mapping all tornado fatalities and killer tornadoes indicates the highest risk associated with
303 tornadoes is felt across the Mid-South. A large swath of high numbers of tornado fatalities and
304 killer tornadoes is seen across central and northern Mississippi and Alabama, and extending from
305 central Arkansas through south-central Tennessee (Fig. 8). When subset by residential structure—
306 permanent homes and mobile homes—it is clear that the average spatial distribution of mobile
307 home fatalities is wider than that of permanent home fatalities, which underscores the high vul-
308 nerability of those structures to tornadoes and the distribution of housing stock across the coun-
309 try. Mobile home fatalities occur throughout much of the Southern Great Plains, Mid-South, and
310 Southeast, while permanent home fatalities occur throughout much of the Southern Great Plains,
311 Midwest, and Mid-South (Fig. 8).

312 4. Discussion

313 Fatalities are the ultimate loss associated with any tornado. Understanding the relationship be-
314 tween risk factors and tornado fatalities has been a long standing goal of previous literature. While
315 we have made substantial gains in making sense of physical, socioeconomic, and demographic fac-
316 tors that increase the number of tornado fatalities, we have not extensively analyzed the differences
317 in tornado fatality rates across physical and social categories. Here, rates across physical and so-

318 cial factors—fatality location, demographic profiles, and year, month, and hour of occurrence—are
319 estimated to gain a deeper understanding of tornado survivability.

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

330 The 24-year per-capita fatality rate is .32% and the per-housing unit fatality rate is .75%. Perhaps
331 unsurprisingly, these rates are slightly lower than those generally found in the most high-impact
332 tornadoes of the past few decades (Biddle 2007; Kuligowski et al. 2013). When considering only
333 killer tornadoes, the fatality rate is higher at both the per-capita and per-housing unit level relative
334 to casualty-producing tornadoes (Fricker 2020a). This is likely due to a combination of smaller
335 numbers and more intense tornadoes (i.e. killer tornadoes are, on average, more powerful than
336 casualty-producing tornadoes). Annual tornado per-capita fatality rates range from a high of 3.9%
337 in 2016 to a low of .06% in 2018, while annual tornado per-housing unit fatality rates range from a
338 high of 8.8% in 2016 to a low of .13% in 2018. Differences in the annual fatality rates might be the
339 result of the interaction between the number of killer tornadoes, the average intensity of the killer
340 tornadoes, and the location in which these storms exist. For example, the low fatality rates in 2018
341 can be explained by a relatively non-active season—9 killer tornadoes—in combination with a

low intensity season—average killer tornado EF-rating of 1.4. Given that tornadoes are becoming increasingly powerful (Elsner et al. 2018b), it is somewhat surprising to see a recent season as the least deadly, though 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, etc.—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 (12:00 a.m.–5:59 a.m.) are twice as deadly as tornadoes during the evening (6:00 p.m.–11:59 p.m.) and three to four times as deadly as tornadoes during the day (6:00 a.m.–5:59 p.m.). 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 down by residential structure—permanent home and mobile home—per-capita and per-housing unit fatality rates are over ten times higher for people sheltering in mobile homes than for people sheltering in perma-

366 nent homes. This result is identical to the findings of Sutter and Simmons (2010), despite having
367 different definitions of fatality rates, and though the risk and vulnerability of mobile home res-
368 idents to the tornado hazard are well established (Boruff et al. 2003; Ashley 2007; Strader and
369 Ashley 2018; Ash et al. 2020), efforts must continue to be made to close the gap between residen-
370 tial structures if the ultimate goal of the community is to reduce the loss of life from tornadoes.
371 That said, these efforts cannot be made in spite of or in place of research that focuses on all tor-
372 nado fatality locations. By placing less emphasis (i.e. research funding) on non-residential tornado
373 fatalities—business, church, school, outside, etc.—it becomes likely that the relationship between
374 residential and non-residential fatalities will continue to evolve, resulting in non-residential fatali-
375 ties accounting for a higher proportion of all tornado fatalities in the future (Fig. 9).

376 The mapping of tornado fatalities throughout a range of factors reveals consistent patterns across
377 space. Unsurprisingly, the Mid-South and Southeast have produced the highest numbers of tor-
378 nado fatalities over the study period, in part, due to the complex blending of physical, social, and
379 economic vulnerabilities. And while the Mid-South and Southeast have long been a region of con-
380 cern for tornado fatalities (Ashley 2007; Fricker et al. 2017b; Agee and Taylor 2019), it appears
381 that the spatial distribution of tornado fatalities in the United States is becoming more concentrated
382 over time. For example, Ashley (2007) finds that the number of tornado fatalities and killer torna-
383 does is highest in the interior South (i.e. Mid-South) from 1985–2005 with small groups of high
384 fatality numbers in the Central Great Plains and Midwest. Here, the vast majority of all tornado
385 fatalities over the period 1995–2018, have occurred in the Mid-South and Southeast with low geo-
386 graphic dispersion in other regions of the country. Nowhere is this pattern more noticeable than in
387 the location of permanent home fatalities, where a large swath of high numbers exists across the
388 Tennessee Valley, in contrast to earlier work (Ashley 2007). Whether or not this concentration of
389 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. 2018b).

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-year 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 is likely—higher-risk tornadoes. Given the length of the SPC historical database, it is also possible to compare annual tornado climatologies to current year activity as a means to select an annual fatality rate—between 1995–2018—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, it should also be noted that high-impact tornadoes play a not insignificant role in the overall fatality rates found in this work. Removing the 2011 Joplin, Missouri tornado from the analysis drops the per-capita fatality rate to .29% and the per-housing unit fatality rate to .68%. It also results in a shift in the relationship between permanent home fatalities and mobile home fatalities

413 to mobile homes having a slightly higher average number of fatalities per year than permanent
414 homes.

415 **5. Conclusions**

416 The United States experiences more tornadoes, on average, than any other country on Earth.
417 As a result, the United States also experiences more tornado fatalities, on average, than any other
418 country on Earth. While previous work on tornado fatalities has largely focused on the number
419 and location of deaths, here, tornado fatalities over the period 1995–2018 are placed in the context
420 of rates—the number of fatalities per person or per-housing unit—and evaluated through multiple
421 physical and social factors to provide a more complete quantitative foundation of tornado fatalities.

422 Over the 24-year study period, the per-capita fatality rate is .32%, while the per-housing unit
423 fatality rate is .75%. By year, 2016 had the highest annual fatality rates and 2018 had the lowest
424 annual fatality rates. By month, July (per-capita) and February (per-housing unit) had the highest
425 fatality rates, while September and October had the lowest fatality rates. By time of year, cold
426 season tornadoes were associated with the highest fatality rates, while late Summer/early Fall
427 tornadoes were associated with the lowest fatality rates. Diurnally, fatality rates at night were
428 twice as high as during the evening and three (per-capita) to four (per-housing unit) times as high
429 as during the day.

430 By location, residential structures accounted for 74% of all tornado fatalities over the period.
431 Broken down further, mobile homes are associated with much higher fatality rates than permanent
432 homes. In fact, one is ten times more likely to die in a mobile home—at both the per-capita and
433 per-housing unit level—than in a permanent home. When these fatality rates are converted to
434 survival rates, the survivability of an individual in a permanent home is estimated at 99.9% at the

435 per-capita level and 99.7% at the per-housing unit level. The survivability of an individual in a
436 mobile home is estimated at 98.7% at the per-capita level and 97% at the per-housing unit level.

437 By age, fatality rates are disproportionately higher for older individuals (over 65) than for any
438 other age group. Indeed, over the study period, an older individual (over 65) is five times more
439 likely to die in a tornado than an individual who is under the age of 18, while an individual between
440 the ages 45 and 64 is twice as likely to die in a tornado than an individual who is between the ages
441 of 18 and 44. By sex, fatality rates are nearly identical between males and females at both the
442 per-capita and per-housing unit level.

443 Mapping tornado fatality locations across space provides further evidence that the Mid-South
444 and Southeast are the regions responsible for the majority of tornado fatalities. Whether subset
445 by season, time of day, or residential structure, the Mid-South and Southeast stand out with the
446 highest number of total fatalities. At the seasonal level, tornado fatalities follow storm activity
447 throughout the year. At the diurnal level, daytime tornado fatalities occur most often across urban
448 centers of the Southern Great Plains and Mid-South, while evening and night fatalities are con-
449 centrated across the Mid-South, extending into the coastal areas of the Southeast and Florida. At
450 the residential level, mobile home fatalities show greater spatial distribution than permanent home
451 fatalities.

452 The utility of these fatality rates is highly dependent on the user. Emergency managers, me-
453 teorologists, and planners might use the rates to better prepare for high-impact events, while re-
454 searchers might use the rates to ground future work. For example, the mapping of fatality locations
455 suggests an increased concentration of tornado fatalities across the Mid-South and Southeast over
456 the past two decades. Future research could leverage the location of tornado fatalities to quantify
457 the impact migration patterns, aging infrastructure, and/or political ecology (e.g. redlining) have

458 on the number or rate of fatalities and whether or not these social factors are as important as phys-
459 ical factors (e.g. increasingly powerful tornadoes) in explaining the tornado fatality landscape.

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

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TABLE 1. Direct Fatality Location Table. Redrafted from Table 3 in National Weather Service (2016).

Location Abbreviation	Location Description	Location Abbreviation	Location Description
BF	Ball Field	MH	Mobile/Trailer Home
BO	Boating	OT	Other/Unknown
BU	Business	OU	Outside/Open Areas
CA	Camping	PH	Permanent Home
CH	Church	PS	Permanent Structure
EQ	Heavy Equipment/Construction	SC	School
GF	Golfing	TE	Telephone
IW	In Water	UT	Under Tree
LS	Long Span Roof	VE	Vehicle and/or Towed Trailer

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

Fatality Location	Number of Tornadoes	Number of Fatalities	Total Population	Total Housing Units
Permanent Home	495	636	502771	113076
Mobile Home	495	671	50987	22168

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	.32%	.75%
Time of Day		
Day (6:00 a.m.–5:59 p.m. CST)	.28%	.60%
Evening (6:00 p.m.–11:59 p.m. CST)	.50%	1.2%
Night (12:00 a.m.–5:59 a.m. CST)	1%	2.4%
Season		
December/January/February	.46%	1.1%
March/April/May	.30%	.70%
June/July/August	.25%	.57%
September/October/November	.31%	.76%
Fatality Location		
Permanent Home	.13%	.30%
Mobile Home	1.3%	3%
Vehicle	.03%	.03%
Age		
Under 18	.15%	.09%
18 to 44	.21%	.19%
45 to 64	.41%	.23%
Over 65	.72%	.21%
Sex		
Male	.32%	.36%
Female	.31%	.37%

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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). The blue line curve is a local regression and the gray band is the 95% uncertainty band on the curve.

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. (D) Per-housing unit fatality rate by hour.

FIG. 3. Tornado fatalities by location. (A) Number of tornado fatalities by location. (B) Number of tornado fatalities by location and year.

FIG. 4. Permanent home and mobile home tornado fatalities. (A) Annual number of tornado fatalities by location. (B) Monthly number of tornado fatalities by location. The blue line curve is a local regression.

FIG. 5. Tornado fatalities by age. (A) Number of tornado fatalities by age. (B) Proportion of tornado fatalities by age. (C) Number of people within killer tornadoes by age. (D) Proportion of people within 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. (D) Tornado fatalities in September, October, and November.

651 FIG. 7. Spatial distribution of tornado fatalities by time of day. (A) Tornado fatalities during the daytime
652 hours (6:00 a.m.–5:59 p.m. CST). (B) Tornado fatalities during the evening and night hours (6:00 p.m.–5:59
653 a.m. CST).

FIG. 8. Spatial distribution of tornado fatalities. (A) Total fatalities. (B) Killer tornadoes. (C) Permanent
home fatalities. (D) Mobile home fatalities.

FIG. 9. Proportion of tornado fatalities occurring in non-residential 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.