1 **Human vulnerability to tornadoes in the United States is highest in**
2 **urbanized areas of the Mid South**

3 James B. Elsner* and Tyler Fricker

4 *Florida State University, Tallahassee, Florida*

5 **Corresponding author address:* James B. Elsner, Department of Geography, Florida State Univer-
6 sity, 113 Collegiate Loop, Tallahassee, FL 32301.

7 E-mail: jelsner@fsu.edu

ABSTRACT

8 Risk factors for tornado casualties are well known. Less understood is how
9 and to what degree these factors, after controlling for strength and the number
10 of people affected, vary over space and time. Here we fit models to casualty
11 counts from all casualty-producing tornadoes during the period 1995–2016 in
12 order to quantify the interactions between population and energy on casualty
13 (deaths plus injuries) rates. Results show that the more populated areas of the
14 Mid South are substantially and significantly more vulnerable to casualties
15 than elsewhere in the country. In this region casualty rates are significantly
16 higher on the weekend. Night and day casualty rates are similar regardless
17 of where the tornadoes occur. States with a high percentage of older people
18 (65+) tend to have greater vulnerability perhaps related to less agility and
19 fewer communication options.

20 **1. Introduction**

21 Nearly one fifth of all natural-hazards fatalities in the United States are the direct result of tor-
22 nadoes (National Oceanic and Atmospheric Administration 2015). A tornado that hits a city is
23 capable of inflicting hundreds or thousands of casualties. Data from the Storm Prediction Center
24 (SPC) of the National Oceanic and Atmospheric Administration (NOAA) show that the 27 April
25 2011 Sawyerville-Eoline, Alabama tornado produced 1564 casualties with 64 of them resulting
26 in death. Less than a month later the 22 May 2011 Joplin, MO tornado produced 1308 casualties
27 with 158 of them resulting in death. More recently, the 26 December 2015 Garland-Rowlett, Texas
28 tornado resulted in 10 deaths and 468 injuries.

29 Casualties occur when a tornado strikes where people live or work. Extreme wind speeds, rela-
30 tively short warning lead times, and the quality of the built environments increase the potential for
31 many casualties (Greenough et al. 2001). Risk factors for a casualty include sheltering in mobile
32 homes, being an older adult, and accessibility to a safe room in a basement or in a reinforced
33 structure (CDC 2012). In fact, early warnings and strong shelters are the most effective way to
34 reduce death and injury (Bohonos and Hogan 1999). Moreover, the potential for a tornado disaster
35 is not uniform across the country (Ashley and Strader 2016). Southern states are particularly vul-
36 nerable to casualties because of the relative abundance of mobile homes and the relative frequency
37 of reduced visibility conditions (trees, hills, and heavy rain).

38 Statistically, given a tornado that produces at least one casualty, the casualty rate (how many
39 people get injured or killed) depends on the number of people in harm's way and on the power of
40 the winds inside the vortex. For an average number of people affected, casualties increase by 33%
41 ($\pm 3\%$) with a doubling of the tornado energy and for an average amount of energy dissipated,
42 casualties increase by 21% ($\pm 3\%$) with a doubling of the number of people affected (Fricker

et al. 2017). Thus as a percentage change, on average, energy is more important of the two in determining the casualty rate. But this finding might only be part of the story as the energy-casualty relationship may vary by population density. Indeed it is has been noted that rural communities are less vulnerable to casualties perhaps due to the unique nature of their social networks and culture (Donner 2007).

Donner (2007) argues that the types of relationships rural communities create, as well as the awareness people in such regions hold of their habitats, might help to protect otherwise vulnerable populations. He argues that perhaps strong social bonds expand the scope and availability of potential sources of weather information, access to shelters, and other resources that help with protective action. He speculates that urban areas are more vulnerable to casualties because of the rare occurrence of tornadoes in urban communities leads to lack of preparedness among residents, along with skepticism about the risks. Further, the presence of tall buildings and other objects may make it difficult to visually confirm the presence of tornadoes in urban communities. Without an environmental cue, warning responses tend to be lower (Mileti and O'Brien 1992).

The goal of this study is to better understand the relationship between tornado energy and casualties as modulated by population. Beyond the direct effects of population and energy on casualties as described in Fricker et al. (2017) it is important to understand possible interactions between these factors. Estimating interactions should help determine when and where communities are *particularly* vulnerable to casualties. For instance, it has been shown that casualty rates are lowest on weekdays when information flows more freely and when there are more robust sheltering-in-place opportunities at school and at work (Zahran et al. 2013).

The present research is grounded in the human ecology of tornado hazards (Boruff et al. 2003). The working hypothesis is that the change in casualties with energy is higher in tornadoes affecting more urbanized areas than more rural areas. The hypothesis arises from previous work suggesting

67 greater vulnerability in cities relative to rural areas (Donner 2007). We define this differential as
68 the rural-urban human vulnerability gradient. We test the hypothesis with a statistical model that
69 includes population density within the tornado path and an estimate of the tornado's total energy
70 dissipation. The objective is to establish statistical estimates of casualty rates as a function of
71 energy across a range of population densities and to examine how these conditional rates might
72 vary across time and space.

73 The statistical approach taken here is similar to that of recent work in examining factors related to
74 tornado casualties (Lim et al. 2017; Zahran et al. 2013; Simmons and Sutter 2008; Donner 2007).
75 However it differs in a couple of key ways. First, we use energy rather than path area, EF rating,
76 or total damage as the indicator of tornado strength. Correlation among these variables is high but
77 energy has a better physical justification as it is the power of the wind that is proximal to the cause
78 of casualties. More importantly, from a statistical perspective, energy is a continuous variable.
79 Second, we exclude tornadoes without casualties focusing instead on the number of casualties
80 given at least one casualty. This makes the modeling simpler and interpretation of results more
81 straightforward since, for a many of reasons, most tornadoes do not result in casualties. The
82 question of whether or not a casualty occurs given a tornado is interesting and has been addressed
83 elsewhere (e.g., Ashley et al. (2008)), but this question is beyond the scope of the present work.
84 With these differences we aim to better statistically explain casualties (higher R^2 values) compared
85 to what has been achieved in the past. Third, the study focuses on the *interaction* between the
86 environmental factor (energy) and the demographic factor (population density) in explaining the
87 rate of casualties. Indeed, the focus on the interaction between the environmental and demographic
88 factors is unique among studies of this type and it provides a new lens with which to view factors
89 that influence the rate of injuries and death from tornadoes.

90 In brief, this study finds that the interaction between population and energy is substantial and
91 statistically significant only in the Mid South including the states of Arkansas, Tennessee, and
92 Missouri. Energy elasticity of casualties is lowest in rural areas and remains low with increasing
93 population with the exception of the Mid South where elasticity in populated areas is significantly
94 higher. The paper continues in Section 2 with a description of the data and the variables used in
95 the analysis and modeling. The casualty model and results are presented in Section 3. The results
96 include an investigation into the variability of the model's interaction term. A discussion of the
97 findings is given in Section 4 followed by a list of conclusions in Section 5. All analysis and
98 modeling are performed using the open-source R language for statistical computing (R Core Team
99 2016) with freely-available data. The R code and links to the data for this study are available at
100 <https://rpubs.com/jelsner/TornadoCasualtyRisk>.

101 **2. Data and Variables**

102 *a. Tornado casualties*

103 Our interest in this work centers on the count of injuries and fatalities in the Storm Prediction
104 Center's tornado database. The database is compiled from the National Weather Service's (NWS)
105 *Storm Data*, and includes all known tornadoes dating back to 1950. A tornado casualty is defined
106 as a fatality or injury directly attributable to a tornado, or impact by airborne, falling, or moving
107 debris. A direct fatality would be a driver killed when a motor vehicle is tossed over. A direct
108 injury requires treatment by a first-responder or treatment at a medical facility. A direct injury
109 would be an person treated for a laceration caused by flying debris. Indirect casualties are not
110 considered. Along with the per-tornado count of deaths and injuries each report includes the
111 straight-line track, start location, damage path dimensions of length and maximum width, and the

112 maximum Enhanced Fujita (EF) rating (damage rating on an ordered scale of categories from zero
113 to five). Reports in the database are compiled by the NWS offices and reviewed by the National
114 Climate Data Center (Verbout et al. 2006). We only consider tornadoes occurring within the
115 conterminous United States.

116 During the 22-year period 1995–2016 there are 26,863 tornadoes recorded in the conterminous
117 United States. Of these, 2,208 are linked to 25,968 casualties. Only 6.7 percent of all casualties
118 lead to death. Most casualty-producing tornadoes result in only a few casualties, while relatively
119 few casualty-producing tornadoes result in many casualties. The Tuscaloosa-Birmingham, Al-
120 abama tornado of 27 April 2011 and the Joplin, Missouri tornado of 22 May 2011 top the list of
121 the most casualties in the period. The Tuscaloosa-Birmingham tornado was one of 362 tornadoes
122 occurring between 25 and 28 April in the largest outbreak in recorded United States history. The
123 Joplin tornado is the deadliest in the modern recorded-keeping era (since 1950).

124 On average a casualty-producing EF0 tornado results in two casualties (Table 1), a casualty-
125 producing EF1 tornado results in 3.1 casualties, and a casualty-producing EF2 tornado results
126 in 6.5 casualties. Big increases in the expected number of casualties occur for the highest rated
127 tornadoes. On average a casualty-producing EF3 tornado results in 20 casualties, a casualty-
128 producing EF4 tornado results in 62 casualties, and a casualty-producing EF5 tornado results in
129 236 casualties.

130 Tornado casualties during the period 1995–2016 are most common across the southeastern quar-
131 ter of the country (Fig. 1). Larger events (more casualties) are associated with worse damage
132 (higher EF rating). The number of casualty-producing tornadoes peaks in the EF1 and EF2 rating
133 categories but the greatest number of casualties peaks in the EF3 and EF4 categories. Casualty-
134 producing EF3+ tornadoes are rare in the West.

Casualty counts are highest in the South. Alabama has the most casualties (3,937) followed by Oklahoma (2,500), Missouri (2,025), Arkansas (1,759), Texas (1,704), and Tennessee (1,678). Rounding out the top ten are Georgia (1,610), Mississippi (1,400), Kentucky (1,051), and North Carolina (985). Massachusetts, ranks 22nd, stands out in New England with 232 casualties from only three tornadoes. Alabama leads the nation in both injuries and deaths with Oklahoma in 2nd with injuries and Missouri in 2nd with deaths (Fig. 2).

b. Population

From the tornado track we create a damage path based on the width variable given in the database and then estimate the total number of people within the path. Population data are obtained from the Gridded Population of the World, version four (GPW, v4) from the Socioeconomic Data and Applications Center at Columbia University, USA. The database contain decennial census density estimates for 1990, 2000, and 2010 represented as people/km². Densities are based on residential population. The native cell resolution is .0083° latitude/longitude, which at 36° N latitude means a cell having the dimension of .9 km in the north-south direction and .7 km in the east-west direction. For each tornado we assign the population density corresponding to the closest decennial estimate so, for example, a tornado that occurred in 1996 uses the 2000 decennial estimate while a tornado that occurred in 2012 uses the 2010 estimate.

For the set of 2208 tornadoes with at least one casualty the median population density per tornado is 31.3 people/km² with an inter-quartile range between 9.6 and 136 people/km². We estimate the EF2 Brooklyn, NY tornado of 8 August 2007 that injured 9 had the highest population density in its path at 13,949 people/km². Of the top ten casualty-producing tornadoes with the highest population densities three occurred in New York, two occurred in Florida, and two occurred in California. Pennsylvania, Massachusetts, and Texas each had one. There are 16 casualty-producing

158 tornadoes that occurred over areas without people highlighting the fact that population data is
159 residential and casualties can occur when people are at work or in transit.

160 The U.S. Census Bureau defines ‘urban’ using population density at the block level. Roughly
161 speaking an urban block has a density of at least 386 people/km² otherwise it is ‘rural’. Here
162 population density is estimated within the tornado path and the rural-urban gradient is defined
163 across a range of densities.

164 The distribution of population and population density in the path of tornadoes by EF rating is
165 shown in Fig. 2. We estimate that about 2.5 million people have been within the path of a tornado
166 and 1.5 million people within the path of a casualty-producing tornado. Because of their frequency
167 and path area, EF1 tornadoes account for the largest accumulated number of people at risk. But
168 given a casualty-producing tornado, it is the EF3 tornadoes that, as a group, affected the most
169 people. The number of people affected is a strong function of EF rating since more damaging
170 tornadoes tend to have larger damage paths (Brooks 2004; Elsner et al. 2014; Ashley and Strader
171 2016) There is no strong relationship between median population density and EF rating. There are
172 thirty non-casualty-producing tornadoes without an EF rating with an estimated total population
173 within the paths of thirteen people.

174 For comparison, Table 3 lists cities and population densities by states in the South.

175 *c. Energy dissipation*

176 Tornadoes dissipate a large amount of atmospheric energy (Fricker et al. 2014, 2017). Following
177 what was done with hurricanes (Emanuel 2005), here per tornado energy dissipation (power) is
178 computed as

$$E = A_p \rho \sum_{j=0}^J w_j v_j^3, \quad (1)$$

where A_p is the area of the path, ρ is area density [1 kg/m^3] v_j is the midpoint wind speed for each rating, and w_j is the corresponding fraction of path area by EF rating. The fraction of path area is that recommended by the U.S. Nuclear Regulatory Commission (see Fricker and Elsner (2015)), which combines a Rankine vortex with empirical estimates (Ramsdell and Rishel 2007). Threshold wind speeds (m s^{-1}) for the EF ratings are a three second gust. With no upper bound on the EF5 wind speeds, the midpoint wind speed is set at 97 m s^{-1} (7.5 m s^{-1} above the threshold wind speed consistent with the EF4 midpoint speed relative to its threshold).

There are no statistically significant upward trends in the annual average per-tornado population exposed or energy dissipated although 2011 was unusually high for both variables (Fig. 3). 2010 was unusually high for energy dissipation, but not population exposed, while 2013 was unusually high for population exposed, but not energy dissipation. The distributions of per-tornado population density and energy dissipation are approximately normal on a logarithmic scale.

3. Results

a. Descriptive statistics

For the set of 2208 tornadoes with at least one casualty the median population density per tornado is 31.3 people/km^2 with an inter-quartile range between 9.6 and 136 people/km^2 . Over the same set of tornadoes the median energy dissipation is 95.5 gigawatt with an inter-quartile range between 14 and 511 GW. The Tallulah-Yazoo City-Durant tornado (Louisiana and Mississippi) of 24 April 2010 that killed ten and injured 146 has the highest energy dissipation at 66.2 PW. There are seven orders of magnitude separating the lowest from the highest per-tornado energy dissipation. There are five orders of magnitude separating the lowest from highest per-tornado population density (Table 4).

201 As shown in Fricker et al. (2017), given a tornado with at least one casualty, the number of
202 casualties increases with the estimated number of people in the path and with the energy dissipation
203 (Fig. 4). The bi-variate relationships are both significant with the casualty-energy relationship
204 stronger.

205 Energy dissipation depends on the EF rating. Tornadoes that hit more targets in developed areas
206 (built environments) have the potential to be rated higher all else being equal because the rating
207 comes from the worst damage. In built environments with more targets there are more people so
208 energy dissipation might contain some population effect. However, the correlation between energy
209 dissipation and population density is small (and negative) indicating this is not a problem.

210 *b. Model*

211 For the set of tornadoes with at least one casualty, the mean and variance of the counts are 11.8
212 and 2826, respectively suggesting a negative binomial model (Simmons and Sutter 2005; Fricker
213 et al. 2017) expressed as

$$C \sim \text{NegBin}(\hat{\mu}, n) \quad (2)$$

214 where $\hat{\mu}$ is the per-tornado casualty rate conditional on at least one casualty and n is the size
215 parameter for the negative binomial distribution.

216 As in Fricker et al. (2017), the logarithm of the casualty rate is expressed statistically as a
217 linear combination of the logarithm of the population density (P) and the logarithm of the energy
218 dissipation (E). Assuming no interaction between population and energy dissipation, Fricker et al.
219 (2017) show that the coefficient on the energy dissipation term (energy elasticity) is significantly
220 larger than the coefficient on the population term. On average a doubling of tornado energy will
221 result in more casualties than a doubling of population. While this result is important in comparing

the relative contributions of tornado energy and population exposure on the casualty rate, it is predicated on the assumption that there is no interaction between them.

Here we relax this assumption and add an interaction term to the model. This allows us to investigate to what extent population *conditions* the effect of energy on the casualty rate. Statistically, the model is expressed as

$$\log(\hat{\mu}) = \hat{\beta}_0 + \hat{\beta}_1 \log(P) + \hat{\beta}_2 \log(E) + \hat{\beta}_3 \log(P) : \log(E) \quad (3)$$

where the coefficients $\hat{\beta}_1$ and $\hat{\beta}_2$ are the population and energy elasticities, respectively and the coefficient $\hat{\beta}_3$ is the coefficient on the interaction term. The model is fit to the set of per-tornado casualties and the coefficients listed in Table 5.

Interest focuses on the interaction term coefficient, which is positive and significant [$\beta_3 = +.22 \pm .049$ (s.e.)] indicating the casualty rate depends on energy dissipation and the casualty rate increases with population density. In short, the effect of energy on the casualty rate (energy elasticity) increases with population (Fig. 5). The energy elasticity is significantly above zero for densities somewhat less than one person/km². For tornadoes affecting more urbanized areas (population densities exceeding 1000 people/km²), energy elasticity is near one. Thus, population conditions the effect of energy on the casualty rate. By symmetry this means energy conditions the effect of population (Berry et al. 2012). The population elasticity is significantly above zero for energy dissipation above about 5 GW and reaches one at about 10 PW of energy dissipation.

The increasing energy elasticity with greater population is quantified in Figure 6 with predictions of the casualty rate at given population densities. For population densities of one person/km² the casualty rate increases from about one at an energy dissipation of .1 GW to about seven at an energy dissipation of 10 PW. For an order of magnitude increase in the number of people under the path, the casualty rate increases from about one at an energy dissipation of .1 GW to about 18

244 at an energy dissipation of 10 PW. For densities at or exceeding 10 people/km² each factor-of-ten
245 increase in energy significantly increases the casualty rate above the previous level.

246 *c. Interaction by state*

247 Here we examine regional variations in the level and significance of the population-energy in-
248 teraction on casualties by refitting the model using tornadoes whose genesis occurred within each
249 state. Table 6 lists the interaction coefficient in decreasing order and the associate p -values by
250 states in states with at least 70 casualty-producing tornadoes. Interaction between energy and
251 population is most pronounced (statistically and substantially) in Arkansas and the surrounding
252 states of the Mid South including Tennessee and Missouri. Marginally significant interaction (p -
253 value $< .15$) is noted for casualties occurring from tornadoes in other states in the South including
254 Kentucky, Oklahoma, Alabama, Mississippi, Texas, and Louisiana, but the effect is less substan-
255 tial. Illinois also has a significant interaction but not North Carolina, Georgia, or Florida. The
256 top ten states by strength of interaction do not change when the threshold number of tornadoes is
257 decreased to 50.

258 To better articulate these regional differences, we compare the conditional energy elasticities
259 between states having substantial and significant interaction (AR, TN, MO) with those having
260 insignificant interaction. That is, we leave out states having significant, but weaker interactions.
261 Results are shown in Figure 7.

262 There is a significant interaction between energy and population on casualties for tornadoes
263 occurring over the Mid South but not elsewhere. In both regions the energy elasticity values for
264 tornadoes over rural areas show about a 25% $[(2^{.32} - 1) \times 100\%]$ increase in the casualty rate for a
265 doubling of energy dissipation. For tornadoes in more urbanized areas primarily across Arkansas,
266 Tennessee, and Missouri a doubling of energy dissipation results in a substantially and significantly

higher increase at about a 300%. In more urban areas across the Great Lakes, Northeast, and parts of the Southeast (Florida and Georgia) a doubling of energy dissipation results in higher casualty rates compared with more rural areas at about 70%, but the difference is not significant. While others have noted that cities can be particular vulnerable to tornado casualties, our result shows that higher urban vulnerability relative to rural vulnerability is largely confined to the Mid South.

d. Day and night casualty rates

The higher casualty rate might be due to the greater percentage of nighttime casualty-producing tornadoes in the Mid South (Ashley et al. 2008). The number of nighttime casualty-producing tornadoes is 878 and the number of daytime casualty-producing tornadoes is 1330. More than one and a half times as many occur between sunrise and sunset as between sunset and sunrise. This is consistent with the diurnal cycle of tornado activity (Ashley et al. 2008), which tends to peak in the late afternoon and early evening hours and is at a minimum in the early morning following the diurnal cycle of convective instability (Kis and Straka 2010). The chance that *any* tornado will produce a casualty is higher at night (Ashley et al. 2008).

Over the period 1995–2016 the empirical probability that a tornado results in at least one casualty is 6.9% between sunrise and sunset but increases to 11.7% between sunset and sunrise and the probability that a tornado results in at least one fatality is 1.3% during the day but increases to 3% at night. However, we note that the per-tornado casualty rate is 12.8 during the day compared to only 10.2 at night. There are 25% fewer casualties, and 11% fewer fatalities, per casualty-producing tornado at night than during the day.

Model results show that casualty rates are not significantly higher at night across a broad range of tornado energies and population exposures (Fig. 8). Stronger tornadoes occurring over less populated areas of the Mid South tend to have a relatively *lower* nocturnal casualty rate. Thus

290 the relatively higher incidence of nocturnal tornadoes across the Mid South does not explain the
291 rural-urban gradient in vulnerability. These day-night results are unaffected by removing the two
292 largest casualty events.

293 *e. Workday and weekend casualty rates*

294 Consistent with expectations based on higher risk information flows during the week and with
295 better access to permanent buildings (businesses and schools), Zahran et al. (2013) showed that
296 tornadoes occurring on workdays are significantly less lethal than those occurring on weekends.
297 We examine this finding for the Mid South. Since weekend days make up fewer than 30% of
298 all days we include the surrounding states of Kentucky, Oklahoma, Alabama, Mississippi, Texas,
299 and Louisiana in our delineation of the Mid South. Model results show that casualty rates are
300 generally lower during the week (Fig. 9) consistent with the findings of Zahran et al. (2013). This
301 is particularly true where there are more people. Interestingly, the weekday-weekend casualty
302 differential exists elsewhere but it is not significant.

303 **4. Discussion**

304 Results from a model of casualties show a substantial and statistically significant variable in-
305 teraction indicating that the percent change with energy in the rate of casualties *increases* with
306 population density. The model reveals a gradient in tornado vulnerability across population den-
307 sity. Fitting separate models using casualty-producing tornadoes originating in each state reveals
308 that vulnerability gradient is significant only in the Mid South. Specifically casualty rates are
309 substantially higher in more urbanized areas of the Mid South than in similar urbanized areas of
310 Indiana or Ohio controlling for energy.

311 As an example, results from the model show that for an average city in Indiana with a population
312 density of 679 people/km² the energy elasticity is 62%. A tornado that causes 10 casualties would
313 cause 16 casualties if it were twice as strong. In contrast for a city like Little Rock, Arkansas
314 with a population density of about the average for the state of Indiana (641 people/km²), the energy
315 elasticity is 225% so a tornado that causes 10 casualties would cause 32 casualties if it were twice
316 as strong. Thus Little Rock, Arkansas is twice as vulnerable to casualties from tornadoes when
317 compared with a similarly sized city (in terms of population density) in Indiana.

318 Additional results arising by fitting the model to subsets of the data show casualty rates are not
319 significantly different at night through a broad range of energy dissipation values and population
320 exposures. The chance of a random tornado producing a casualty is apparently higher at night
321 but the casualty rate per casualty-producing tornado is somewhat lower. Thus the higher relative
322 incidence of nocturnal tornadoes across the Mid South does not explain the rural-urban gradient
323 in vulnerability. Also, casualty rates are *higher* during the weekend than during the week but the
324 differential is only substantial and significant in more urbanized areas in the Mid South.

325 While the approach taken here is able to articulate tornado vulnerability in terms of casualty
326 rates while controlling for tornado strength, the findings are largely consistent with others. For
327 instance, Donner (2007) finds that census tracts with larger proportion of rural residents tend to
328 be less vulnerable to fatalities and injuries. Results here show the same. Tornadoes occurring
329 over rural areas are less vulnerable (as a percentage change for a change in energy) than areas
330 with more people. But this rural-urban vulnerability gradient is confined to the Mid South and
331 is most significant only for Arkansas, Tennessee, and Missouri. As mentioned, Donner (2007)
332 speculates that the culture of rural America might foster better resilience. However, findings here
333 show that more urbanized areas have the same vulnerability as rural areas except in the Mid South
334 so the explanation is, at best, incomplete. He further suggests that urban areas might have greater

335 vulnerability due to the presence of the built environment, which limits visibility and thus the
336 potential for visual confirmation. Again, this explanation would not predict the absence of a
337 significant rural-urban vulnerability gradient in tornadoes occurring outside the Mid South.

338 Also, Zahran et al. (2013) finds that tornado casualties are more common over the weekend.
339 Results here show the same. On average, in regions where population densities exceed 100
340 people/km², significantly higher casualty rates are found during the weekend than during the week.
341 But this statistically significant daily variation is confined to the greater Mid South. The most
342 common protective measure against a tornado casualty is to shelter-in-place. Donner (2007) and
343 Zahran et al. (2013) speculate that work and school buildings provide a more substantial place to
344 shelter than at home during the weekend and that risk information is more efficiently communi-
345 cated at work and school. However, we find that casualty rates are somewhat higher during the day
346 than at night when folks are more likely to be at home, so these explanations are incomplete. Most
347 motor vehicle fatalities involving tornadoes occur in the South (Paulikas and Schmidlin 2017), but
348 folks living in rural areas drive greater distances than those in towns or cities and more driving is
349 done during the week than on weekends (Triplett et al. 2015).

350 According to Zahran et al. (2013), the daily variation in casualty rates should be lower during
351 the summer with the increasing loss of risk information, and when people are less likely to be in
352 tornado-resistant buildings like businesses and schools. But, since his model does not account for
353 spatial variability, this result is explained by the northward migration of tornadoes to areas outside
354 the Mid South during the summer where there is less difference between weekdays and weekends.
355 Further the results here show that Illinois and Alabama have statistically similar model coefficients
356 indicating that different coping mechanisms for people in the South (Sims and Baumann 1972) are
357 likely not a significant factor in casualty rates more recently.

Mobile homes are particularly dangerous in a tornado with the likelihood of casualties substantially higher than in a permanent home (Glass et al. 1980; Eidson et al. 1990; Brooks and Doswell 2002; Simmons and Sutter 2005; Ashley et al. 2008). While there are more people living in manufactured homes in the South than elsewhere (Ashley 2007), the attribution of the rural-urban tornado vulnerability gradient to mobile home frequency is problematic. First, according to Sutter and Simmons (2010) just two states, Florida and Georgia, account for 30% of all mobile home tornado fatalities in the United States. Neither Florida nor Georgia have a substantial rural-urban vulnerability gradient. Second, South Carolina and North Carolina have the largest percentage of mobile homes (ACS 2004) but not substantial vulnerability gradients. Finally, the percentage of manufactured homes is higher in areas with lower population density (Nitschke 2004), a gradient that is directed opposite to the direction of the vulnerability gradient. Thus while mobile homes are certainly a significant factor in explaining tornado casualties, their spatial distribution does not explain the spatial distribution of the vulnerability gradient.

a. Suburban and exurban elderly

Why are urbanized areas in the Mid South more vulnerable to tornado casualties than rural areas there and elsewhere? Age increases the odds of getting hurt or killed in a tornado (Glass et al. 1980; Eidson et al. 1990; Brown et al. 2002) and hurricane (Brunkard et al. 2008) and may help with the explanation. The percentage of fatalities of those over age 50 is higher than the percent of the population of that age (Merrell et al. 2005; Ashley 2007). According to Paul and Stimers (2014) the elderly (65 yr and older) accounted for more than a third of tornado fatalities in the 22 May 2011 Joplin, MO tornado. The percentage of elderly in Joplin was 14.8% (2010) but they experienced more than three times as many deaths as the total population of this cohort (Paul and Stimers 2014). According to the National Centers for Environmental Information more than 71%

381 of the fatalities in the Joplin tornado were people 45 years old or older. In contrast 50% of the
382 fatalities in the Tuscaloosa-Birmingham tornado were people in that same age range (National
383 Centers for Environmental Information 2017).

384 Arkansas and Missouri rank high in the percentage of people over 65 (Table 5). Tennessee is near
385 the middle. Georgia is very low and so is Louisiana. The spatial distribution of percent elderly
386 appears to match the spatial distribution of the rural-urban vulnerability gradient. Indeed, the
387 correlation between the percent elderly given in the 2010 Census (Howden and Meyer 2011) and
388 the interaction coefficient in the casualty model across the twelve states with at least 70 casualty-
389 producing tornadoes is $+.69$ [$+.19$, $+.90$, 95% uncertainty interval]. The percentage of disabled
390 (under 65) is also positively correlated with vulnerability suggesting that personal mobility might
391 be one casual factor.

392 But state-level demographics can be misleading as the results show that it is the more urbanized
393 areas with the greater vulnerability. The 2010 census data for the number of elderly in towns and
394 cities with at least 10,000 people and using a threshold of 18% for percent 65+ shows there are
395 33 cities/towns in the four states of the Mid South (Arkansas, Tennessee, Missouri, and Kentucky)
396 meeting these criteria compared to only 15 in the four states of the South (Georgia, Alabama,
397 Mississippi, and Louisiana). The total elderly in these more urbanized areas total 125,198 and
398 48,720 for the Mid South and South, respectively.

399 Being elderly is a statistical determinant of tornado vulnerability. If there is causality it might
400 be related to older people being less mobile and more likely to have health issues (Dixon and
401 Moore 2012; Cutter et al. 2000; Kilijaneek and Drabek 1979) limiting their ability to seek adequate
402 shelter and to perform labor intensive measures related to prevention. Moreover, elderly living on
403 fixed incomes may lack the financial resources needed to upgrade their homes to better withstand
404 tornado winds. With an aging population and more folks retiring to the South (not just to Florida)

405 vulnerability might well increase in the future. Indeed over the past seven years casualty rates have
406 decreased across the United States but not across the Mid South (Fig 10).

407 **5. Conclusions**

408 Tornado casualty counts from the SPC tornado record over the period 1995–2016 are fit to a
409 model with total energy dissipation and population density under the path as independent variables.
410 Model results quantify the interactions between population and energy on tornado casualty counts
411 elucidating where and when communities are particularly vulnerable. The main findings are:

- 412 • More urbanized areas of the Mid South are substantially and significantly more vulnerable to
413 casualties from tornadoes than elsewhere in the country.
- 414 • Casualty rates are significantly higher during the weekend for tornadoes occurring over the
415 Mid South, but not elsewhere.
- 416 • Night and day casualty rates are similar regardless of where they occur.
- 417 • At the state level, increased vulnerability to casualties from tornadoes occurring in more
418 urbanized areas correspond with higher percentages of elderly people.

419 This is the first study to examine the *interaction* of population and tornado strength on tornado
420 casualties. To better articulate vulnerable subpopulations future work will focus on quantifying the
421 interaction of specific demographics and tornado strength and how those interactions vary spatially
422 and temporally.

423 *Acknowledgments.* This work was initiated after discussions with William D. Berry in the De-
424 partment of Political Science at Florida State University.

References

- ACS, 2004: Percent of housing units that are mobile homes by state. Tech. rep., American Community Survey. URL www.statemaster.com/graph/hou_per_of_hou_uni_tha_are_mob_hom-housing-percent-units-mobile-homes#.
- Ashley, W., 2007: Spatial and temporal analysis of tornado fatalities in the United States: 1880–2005. *Weather and Forecasting*, **22**, 1214–1228.
- Ashley, W. S., A. J. Krmenc, and R. Schwantes, 2008: Vulnerability due to nocturnal tornadoes. *Weather and Forecasting*, **23**, 795–807.
- Ashley, W. S., and S. M. Strader, 2016: Recipe for disaster: How the dynamic ingredients of risk and exposure are changing the tornado disaster landscape. *Bulletin of the American Meteorological Society*, **97**, 767–786.
- Berry, W. D., M. Golder, and D. Milton, 2012: Improving tests of theories positing interaction. *The Journal of Politics*, **74** (3), 653–671, doi:10.1017/S0022381612000199.
- Bohonos, J. J., and D. E. Hogan, 1999: The medical impact of tornadoes in North America. *The Journal of Emergency Medicine*, **17**, 67–73.
- Boruff, B. J., J. A. Easoz, S. D. Jones, H. R. Landry, J. D. Mitchem, and S. L. Cutter, 2003: Tornado hazards in the United States. *Climate Research*, **24**, 103–117.
- Brooks, H. E., 2004: On the relationship of tornado path length and width to intensity. *Weather and Forecasting*, **19**, 310–319.
- Brooks, H. E., and C. A. Doswell, 2002: Deaths in the 3 May 1999 Oklahoma City tornado from a historical perspective. *Weather and Forecasting*, **17**, 354–361.

446 Brown, S., P. Archer, E. Kruger, and S. Mallonee, 2002: Tornado-Related Deaths and Injuries in
 447 Oklahoma due to the 3 May 1999 Tornadoes. *Weather and Forecasting*, **17**, 343–353.

448 Brunkard, J., G. Namulanda, and R. Ratard, 2008: Hurricane katrina deaths, louisiana, 2005.
 449 *Disaster Medicine and Public Health Preparedness*, **2** (4), 215–223, doi:10.1097/DMP.
 450 0b013e31818aaf55.

451 CDC, 2012: Tornado-Related Fatalities Five States, Southeastern United States, April 2528, 2011.
 452 Tech. rep., Centers for Disease Control and Prevention. URL [www.cdc.gov/mmwr/preview/](http://www.cdc.gov/mmwr/preview/mmwrhtml/mm6128a3.htm)
 453 [mmwrhtml/mm6128a3.htm](http://www.cdc.gov/mmwr/preview/mmwrhtml/mm6128a3.htm).

454 Cutter, S., J. T. Mitchell, and M. S. Scott, 2000: Revealing the vulnerability of people and places:
 455 A case study of Georgetown County, South Carolina. *Annals of the Association of American*
 456 *Geographers*, **90**, 13–37.

457 Dixon, R. W., and T. W. Moore, 2012: Tornado vulnerability in Texas. *Weather, Climate, and*
 458 *Society*, **4**, 59–68.

459 Donner, W. R., 2007: The political ecology of disaster: An analysis of factors influencing U.S.
 460 tornado fatalities and injuries, 1998–2000. *Demography*, **44** (3), 669–685, doi:10.1353/dem.
 461 2007.0024, URL <https://doi.org/10.1353%2Fdem.2007.0024>.

462 Eidson, M., J. A. Lybarger, J. E. Parsons, J. N. MacCormack, and J. I. Freeman, 1990: Risk factors
 463 for tornado injuries. *International Journal of Epidemiology*, **19**, 1051–1056.

464 Elsner, J. B., T. H. Jagger, H. M. Widen, and D. R. Chavas, 2014: Daily tornado frequency distri-
 465 butions in the United States. *Environmental Research Letters*, **9** (2), 024 018.

466 Emanuel, K., 2005: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*,
 467 **436**, 686–688.

468 Fricker, T., and J. B. Elsner, 2015: Kinetic energy of tornadoes in the United States. *PLoS ONE*,
 469 **10**, e0131090, doi:10.1371/journal.pone.0131090.

470 Fricker, T., J. B. Elsner, P. Camp, and T. H. Jagger, 2014: Empirical estimates of kinetic energy
 471 from some recent U.S. tornadoes. *Geophysical Research Letters*, **41**, 4340–4346.

472 Fricker, T., J. B. Elsner, and T. H. Jagger, 2017: Population and energy elasticity of tornado
 473 casualties. *Geophysical Research Letters*, **44**, 3941–3949, doi:10.1002/2017GL073093.

474 Glass, R. I., R. B. Craven, D. J. Bregman, B. J. Stoll, N. Horowitz, P. Kerndt, and J. Winkle, 1980:
 475 Injuries from the Wichita Falls tornado: Implications for prevention. *Science*, **207**, 734–738.

476 Greenough, G., M. McGeehin, S. M. Bernard, J. Trtanj, J. Riad, and D. Engelbert, 2001: The
 477 potential impacts of climate variability and change on health impacts of extreme weather events
 478 in the United States. *Environmental Health Perspectives*, **109**, 191–198.

479 Howden, L. M., and J. A. Meyer, 2011: Age and sex composition: 2010. Tech. rep., United States
 480 Census Bureau. URL <https://www.census.gov/population/www/socdemo/age/>.

481 Kilijanek, T., and T. Drabek, 1979: Assessing long-term impacts of a natural disaster: A focus on
 482 the elderly. *Gerontologist*, **19**, 555–566.

483 Kis, A. K., and J. M. Straka, 2010: Nocturnal tornado climatology. *Weather and Forecasting*,
 484 **25** (2), 545–561.

485 Lim, J., S. Loveridge, R. Shupp, and M. Skidmore, 2017: Double danger in the double wide:
 486 Dimensions of poverty, housing quality and tornado impacts. *Regional Science and Urban*
 487 *Economics*, **65**, 1–15, doi:10.1016/j.regsciurbeco.2017.04.003, URL [https://doi.org/10.1016/j.](https://doi.org/10.1016/j.regsciurbeco.2017.04.003)
 488 [regsciurbeco.2017.04.003](https://doi.org/10.1016/j.regsciurbeco.2017.04.003).

489 Merrell, D., K. M. Simmons, and D. Sutter, 2005: The determinants of tornado casualties and the
 490 benefits of tornado shelters. *Land Economics*, **81**, 87–99.

491 Mileti, D. S., and P. W. O’Brien, 1992: Warnings during disasters: Normalizing communicated
 492 risk. *Social Problems*, **39**, 40–57.

493 National Centers for Environmental Information, 2017: Storm Events Database. URL {[https://](https://www.ncdc.noaa.gov/stormevents/)
 494 www.ncdc.noaa.gov/stormevents/}.

495 National Oceanic and Atmospheric Administration, 2015: National Weather Service Weather Fa-
 496 tality, Injury, and Damage Statistics. URL {[http://www.nws.noaa.gov/om/hazstats/resources/](http://www.nws.noaa.gov/om/hazstats/resources/weather_fatalities.pdf)
 497 [weather_fatalities.pdf](http://www.nws.noaa.gov/om/hazstats/resources/weather_fatalities.pdf)}.

498 Nitschke, L., 2004: Manufactured homes a big factor in rural homeownership in U.S.
 499 Tech. rep., Population Reference Group. URL [www.prb.org/Publications/Articles/2004/](http://www.prb.org/Publications/Articles/2004/ManufacturedHomesaBigFactorinRuralHomeownershipinUS.aspx)
 500 [ManufacturedHomesaBigFactorinRuralHomeownershipinUS.aspx](http://www.prb.org/Publications/Articles/2004/ManufacturedHomesaBigFactorinRuralHomeownershipinUS.aspx).

501 Paul, B. K., and M. Stimers, 2014: Spatial analyses of the 2011 Joplin tornado mortality: Deaths
 502 by interpolated damage zones and location of victims. *Weather, Climate, and Society*, **6**, 161–
 503 174.

504 Paulikas, M. J., and T. W. Schmidlin, 2017: US tornado fatalities in motor vehicles (19912015).
 505 *Natural Hazards*, **87**, 121–143.

506 R Core Team, 2016: *R: A Language and Environment for Statistical Computing*. Vienna, Austria,
 507 R Foundation for Statistical Computing, URL <https://www.R-project.org/>.

508 Ramsdell, J. V., Jr, and J. P. Rishel, 2007: Tornado Climatology of the Contiguous United States.
 509 Tech. Rep. NUREG/CR-4461, PNNL-15112, Pacific Northwest National Laboratory, P.O. Box
 510 999, Richland, WA 99352.

511 Simmons, K. M., and D. Sutter, 2005: WSR-88d radar, tornado warnings, and tornado casual-
 512 ties. *Weather and Forecasting*, **20** (3), 301–310, doi:10.1175/waf857.1, URL [https://doi.org/10.](https://doi.org/10.1175%2Fwaf857.1)
 513 [1175%2Fwaf857.1](https://doi.org/10.1175%2Fwaf857.1).

514 Simmons, K. M., and D. Sutter, 2008: Tornado warnings, lead times, and tornado casualties: An
 515 empirical investigation. *Weather and Forecasting*, **23**, 246–258.

516 Sims, J. H., and D. D. Baumann, 1972: The tornado threat: Coping styles of the North and South.
 517 *Science*, **176**, 1386–1392.

518 Sutter, D., and K. M. Simmons, 2010: Tornado fatalities and mobile homes in the United States.
 519 *Natural Hazards*, **53**, 125–137.

520 Triplett, T., R. Santos, and S. Rosenbloom, 2015: American Driving Survey: Method-
 521 ology and Year 1 Results, May 2013–2014. Tech. rep., The Urban Institute. URL
 522 [http://newsroom.aaa.com/wp-content/uploads/2015/04/REPORT_American_Driving_Survey_](http://newsroom.aaa.com/wp-content/uploads/2015/04/REPORT_American_Driving_Survey_Methodology_and_year_1_results_May_2013_to_May_2014.pdf)
 523 [Methodology_and_year_1_results_May_2013_to_May_2014.pdf](http://newsroom.aaa.com/wp-content/uploads/2015/04/REPORT_American_Driving_Survey_Methodology_and_year_1_results_May_2013_to_May_2014.pdf).

524 Verbout, S. M., H. E. Brooks, L. M. Leslie, and D. M. Schultz, 2006: Evolution of the U.S. tornado
 525 database: 1954–2003. *Weather and Forecasting*, **21**, 86–93.

526 Zahran, S., D. Tavani, and S. Weiler, 2013: Daily variation in natural disaster casualties: Informa-
 527 tion flows, safety, and opportunity costs in tornado versus hurricane strikes. *Risk Analysis*, **33**,
 528 1265–1280.

529

530

531

532

533

534

535

536

537

LIST OF TABLES

Table 1. Casualties by EF rating. 27

Table 2. Distribution of population and population density in the path of tornadoes
(casualty-producing and all) by EF rating. 28

Table 3. Example towns and cities by state across a range of population densities. 29

Table 4. Descriptive statistics for the variables used in the regression model. MW:
megawatt (10^6 W), GW: gigawatt (10^9 W), TW: terawatt (10^{12} W) 30

Table 5. Table of coefficients for a model fit to the per-tornado casualty counts. 31

Table 6. Interaction coefficients and associated p -value by state. 32

TABLE 1. Casualties by EF rating.

EF	Casualties	Tornadoes	Fatalities	Injuries	Avg. Casualties/Tor.
0	362	183	8	354	2.0
1	2300	750	79	2221	3.1
2	4888	753	218	4670	6.5
3	7933	392	536	7397	20.2
4	7187	116	457	6730	62.0
5	3298	14	432	2866	235.6

538 TABLE 2. Distribution of population and population density in the path of tornadoes (casualty-producing and
539 all) by EF rating.

EF	Tornadoes	Total People	Avg. No. People/Tor	Median No. People/Tor	Avg. Pop. Density (/km ²)	Median Pop. Density (/km ²)
Casualty-Producing Tornadoes						
0	183	9386	51	4	440	55
1	750	217053	289	17	293	37
2	753	397781	528	72	186	29
3	392	492471	1256	261	88	24
4	116	289722	2498	824	103	27
5	14	89981	6427	3318	82	25
All Tornadoes						
0	16453	196183	12	0	128	5
1	7463	698008	94	5	139	14
2	2143	633813	296	29	119	15
3	620	555967	897	125	77	17
4	140	294953	2107	550	91	18
5	14	89981	6427	3318	82	25

TABLE 3. Example towns and cities by state across a range of population densities.

State	Towns/Cities			
	1-10 people/km ²	10-100 people/km ²	100-500 people/km ²	500-1000 people/km ²
Arkansas	Scott (8.4)	Zinc (64)	Jonesboro (357)	Little Rock (632)
Tennessee	Flat Top Mountain (9.5)	Hillsboro (42)	Gatlinburg (129)	Memphis (770)
Missouri	Champ (6.2)	Rensselaer (44)	Clinton (380)	Columbia (660)
Alabama	Putnam (7.9)	Hackleburg (37)	Montgomery (478)	Birmingham (551)
Mississippi	NA	McLain (49)	Starkville (360)	Oxford (730)
Louisiana	Lisbon (5.4)	Monterey (60)	Abita Springs (203)	Lafayette (950)
Georgia	Cedar Springs (9.6)	Bluffton (28)	Milledgeville (348)	Albany (535)
Oklahoma	Sweetwater (2.1)	Elmer (87)	Norman (255)	Stillwater (620)

540 TABLE 4. Descriptive statistics for the variables used in the regression model. MW: megawatt (10^6 W), GW:
541 gigawatt (10^9 W), TW: terawatt (10^{12} W)

	Variable	Value
	Number of Tornadoes	2192
	Average number of casualties per tornado	12
	Highest number of casualties	1564
	Lowest number of casualties	1
	Standard deviation of casualties	53
	Average population density per tornado (people/km ²)	223
	Greatest population density (people/km ²)	13949
	Least population density (people/km ²)	0
	Standard deviation of population density (people/km ²)	708
	Average energy dissipation per tornado (GW)	855
	Maximum energy dissipation (TW)	66
	Minimum energy dissipation (MW)	5.7
	Standard deviation of energy dissipation (TW)	2.9

TABLE 5. Table of coefficients for a model fit to the per-tornado casualty counts.

	Estimate	Std. Error	t value	$\Pr(> t)$
$\hat{\beta}_0$	-3.0268	0.9606	-3.15	0.0016
$\hat{\beta}_1$	-1.8700	0.5281	-3.54	0.0004
$\hat{\beta}_2$	0.3825	0.0868	4.41	< 0.0001
$\hat{\beta}_3$	0.2200	0.0488	4.51	< 0.0001

TABLE 6. Interaction coefficients and associated p -value by state.

Rank	State	$\hat{\beta}_1$	$\hat{\beta}_1$	$\hat{\beta}_3$	p -value
1	Arkansas	-11.353	-0.207	1.023	0.000
2	Tennessee	-7.105	-0.288	0.717	0.001
3	Missouri	-5.965	0.084	0.607	0.010
4	Kentucky	-5.021	0.173	0.493	0.053
5	Illinois	-4.111	0.271	0.417	0.021
6	Oklahoma	-3.625	0.315	0.404	0.023
7	Alabama	-3.007	0.499	0.347	0.056
8	Mississippi	-3.291	0.454	0.329	0.106
9	Texas	-2.844	0.135	0.308	0.001
10	North Carolina	-2.790	-0.002	0.286	0.458
11	Louisiana	-2.060	0.506	0.246	0.126
12	Georgia	-0.920	0.450	0.128	0.663

		2010		2016
	State	β_3	Percent Elderly (65+)	Percent Elderly (65+)
1	Arkansas	1.02	14.4	16.3
2	Tennessee	0.72	13.4	15.7
3	Missouri	0.61	14.0	16.1
4	Kentucky	0.49	13.3	15.6
5	Illinois	0.42	12.5	16.1
6	Oklahoma	0.40	13.5	15.0
7	Alabama	0.35	13.8	16.1
8	Mississippi	0.33	12.8	15.1
9	Texas	0.31	10.3	12.0
10	North Carolina	0.29	12.9	15.5
11	Louisiana	0.25	12.3	14.4
12	Georgia	0.13	10.7	13.1

542	LIST OF FIGURES	
543	Fig. 1.	Location of casualty-producing tornadoes (1995–2016) by EF rating. The size of the circle is proportional to the number of casualties. 35
544		
545	Fig. 2.	Tornado casualties (top: injuries, bottom: fatalities) by state (1995-2016). All casualties are assigned to the state in which genesis occurred. 36
546		
547	Fig. 3.	People exposed and energy dissipation for all casualty-producing tornadoes (1995-2016). (A) Annual average number of people exposed per tornado, (B) distribution of per tornado population density, (C) annual average energy dissipation per tornado, and (D) distribution of per tornado energy dissipation. 37
548		
549		
550		
551	Fig. 4.	Casualties versus population density (A) and energy dissipation (B). 38
552	Fig. 5.	Marginal effect of (A) population on energy elasticity and (B) energy on population elasticity. The gray ribbon indicates the 95% uncertainty bound on the slope. Relative percentage of observations are shown as a histogram along the horizontal axis. 39
553		
554		
555	Fig. 6.	Predicted effect of energy dissipation on casualties for given levels of population density. The vertical lines indicate the 95% uncertainty bounds. 40
556		
557	Fig. 7.	The effect of energy on casualties conditional on population across the Mid South (A) and elsewhere (B). The gray ribbon indicates the 95% uncertainty bound on the slope. 41
558		
559	Fig. 8.	Predicted casualty rates daytime versus nighttime for the Mid South (A) and all states (B). The vertical lines indicate the 95% uncertainty bounds. 42
560		
561	Fig. 9.	Predicted casualty rates on week days and on weekends for the greater Mid South (A) and elsewhere (B). The vertical lines indicate the 95% uncertainty bounds. 43
562		
563	Fig. 10.	Predicted casualty rates for a tornado with 1 GW of energy dissipation over an area with a population density of 300 people/km ² . The vertical lines indicate the 95% uncertainty bounds. 44
564		
565		

566 FIG. 1. Location of casualty-producing tornadoes (1995–2016) by EF rating. The size of the circle is propor-
 567 tional to the number of casualties.

FIG. 2. Tornado casualties (top: injuries, bottom: fatalities) by state (1995-2016). All casualties are assigned to the state in which genesis occurred.

FIG. 3. People exposed and energy dissipation for all casualty-producing tornadoes (1995-2016). (A) Annual average number of people exposed per tornado, (B) distribution of per tornado population density, (C) annual average energy dissipation per tornado, and (D) distribution of per tornado energy dissipation.

FIG. 4. Casualties versus population density (A) and energy dissipation (B).

FIG. 5. Marginal effect of (A) population on energy elasticity and (B) energy on population elasticity. The gray ribbon indicates the 95% uncertainty bound on the slope. Relative percentage of observations are shown as a histogram along the horizontal axis.

576

FIG. 6. Predicted effect of energy dissipation on casualties for given levels of population density. The vertical

577

lines indicate the 95% uncertainty bounds.

578 FIG. 7. The effect of energy on casualties conditional on population across the Mid South (A) and elsewhere
 579 (B). The gray ribbon indicates the 95% uncertainty bound on the slope.

FIG. 8. Predicted casualty rates daytime versus nighttime for the Mid South (A) and all states (B). The vertical lines indicate the 95% uncertainty bounds.

FIG. 9. Predicted casualty rates on week days and on weekends for the greater Mid South (A) and elsewhere (B). The vertical lines indicate the 95% uncertainty bounds.

584 FIG. 10. Predicted casualty rates for a tornado with 1 GW of energy dissipation over an area with a population
585 density of 300 people/km². The vertical lines indicate the 95% uncertainty bounds.