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Projected 21st century changes in tornado exposure, risk, and disaster potential

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Abstract While risk and associated hazard characteristics are important components of disaster formation, the consequences of hazards are often driven by underlying human and built-environment vulnerabilities. Yet, there has been little research conducted on how the evolving contributors of risk and vulnerability commingle to produce disaster potential. In this study, we assess the interaction of risk and vulnerability by investigating a single hazard, the tornado. How future changes in risk and vulnerability influence tornado disaster probability is estimated by integrating, for the first time, projected residential built environment data and modeled future severe weather environments. Results suggest that, although the projected twenty-first century escalation in tornado risk will play a role in increasing disaster consequences and frequency, growth in the human-built environment is projected to outweigh the effects of increased risk on future tornado disaster potential. While changes in societal exposure are projected to overshadow potential climate change-driven alterations in tornado risk, the combination of both an increase in risk and exposure may lead to a threefold increase in median annual tornado impact magnitude and disaster potential from 2010 to 2100.

1 Introduction and background

The increasing frequency and consequences of weather-related disasters have been documented and examined in recent years; yet, identifying the attribution of this increase continues to challenge scholars and spark intense debate in the media (Huggel et al.

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2013; Mohleji and Pielke 2014; Pielke 2014; NAS 2016). Broadly, weather-related disasters are a function of both climate and society (Changnon et al. 2000; Bouwer 2011, 2013; IPCC 2012, 2014). While the climate, or risk, of severe thunderstorms may be changing (Brooks 2013; Tippett et al. 2015), amplified exposure due to societal change and economic growth is considered to be an important factor in increasing disaster impacts (Kunkel et al. 1999; Pielke 2005; Hoppe and Pielke 2006; Bouwer 2011; IPCC 2012, 2014; Mohleji and Pielke 2014; Visser et al. 2014), especially for tornadoes (Brooks and Doswell 2003a; Simmons et al. 2013; Ashley et al. 2014; Visser et al. 2014; Ashley and Strader 2016).

Prior investigations (Dixon and Moore 2012; Rosencrants and Ashley 2015; Ashley and Strader 2016) have examined elements of both societal exposure and tornado risk, but the scale of analysis, data fidelity, limited period of record, and the complexity of the interactions of these constituents constrained the extent of findings, especially for future possibilities. Recently, there has been an increase in research exploring potential changes in severe weather risk through global climate models and additional nesting and downscaling techniques (Trapp et al. 2007; Diffenbaugh et al. 2013; Gensini and Mote 2014; Trapp and Hoogewind 2016). However, no studies have assessed the potential of tornado disasters in the future while examining *both* disaster ingredients of risk and exposure. Highlighting the importance of considering both the effects of changing risk and exposure, Janković and Schultz (2016) suggest that societal exposure may overshadow the effects of climate-change-driven alterations in hazard risk on future disaster damage and losses. Indeed, Bouwer (2013) and Huggel et al. (2013) remark, respectively, that “it is striking” that most of the previous research assessing impacts does not consider changes in exposure as an important driver of changes in the disaster landscape and that the concept of risk is not used in a coherent way in research concerned with attribution of extreme events and disasters to climate change. How do risk and exposure disaster components interplay and, as each change, will their interaction lead to greater probabilities of future disaster? Is risk or the vulnerability constituent of exposure the greater contributor to this change in potential?

In this study, we assess these questions by examining, for the first time, estimates of future tornado hazards with forecast residential built environment data and modeled future severe weather environments. Specifically, an experimental control framework is employed to examine to how the changing constituents of human exposure and tornado risk may be “loading the disaster dice,” establishing expectations of future societal impacts within the high tornado risk regions in the US (Fig. 1).

Many terms in hazard science—such as risk, vulnerability, disaster, and impacts—have a variety of definitions and are difficult to measure at fine spatial scale (Paul 2011). We equate tornado vulnerability to its fundamental physical characteristic, exposure. Although disasters are driven principally by extreme events interacting with human, social, and physical vulnerabilities, we define *disaster* as a quantitative measure of the number of housing units (HUs) potentially damaged or destroyed by a tornado (Ashley and Strader 2016; Strader et al. 2016a). In addition, the study assumes that the greater the number of homes potentially affected by a tornado, the greater the tornado disaster magnitude. Tornado or HU “impacts” are also designated as the total number of homes potentially damaged by a simulated tornado path. Lastly, the probability of a hazard occurring in space and time with varying characteristics (e.g., tornado width, length, magnitude, direction, location) determines tornado *risk*.

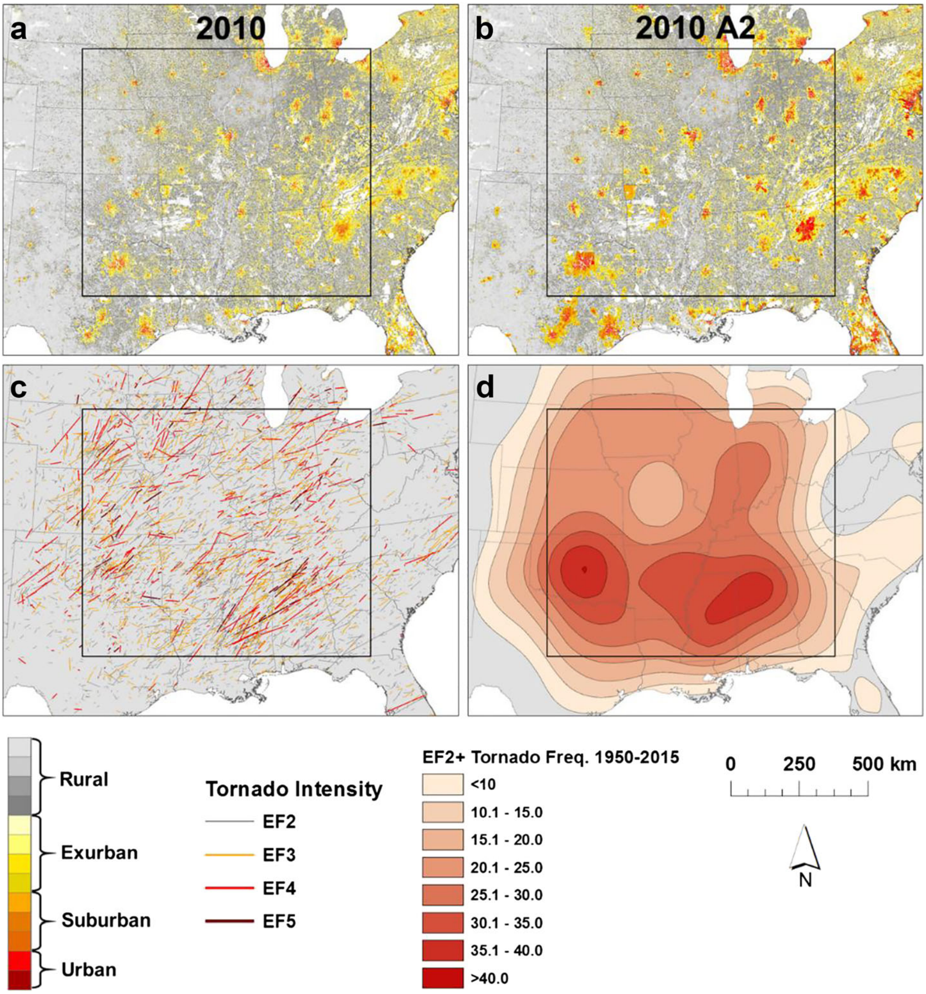

Fig. 1 Study domain (*black box*) illustrated with **a** 2010 housing unit (HU) exposure surface, **b** 2100 (A2) HU exposure surface, **c** all EF2+ tornado paths from 1950 to 2015, and **d** low-pass filtered EF2+ tornado path frequency from 1950 to 2015

2 Methodology

2.1 Spatially Explicit Regional Growth Model and Integrated Climate and Land Use Scenarios

The Spatially Explicit Regional Growth Model (SERGoM) and Integrated Climate and Land Use Scenarios (ICLUS) HU projections were employed to approximate future changes in societal exposure to significant (EF2 and greater on the enhanced Fujita scale) tornadoes because US decennial census geographical units of aggregation differ from one census to another at the finest spatial scale (block-level). In addition, block-level enumerations are also temporally restricted (i.e., available solely from 1990 onward across the conterminous US). The SERGoM was partly developed to control for these shortcomings with its output consisting of gridded, decadal, fine-scale (100-m) historical HU density projections across the conterminous US for the years of 1940 through 2000 (Theobald 2005). SERGoM HU estimate accuracy and bias was measured with a hindcast technique using the US Census Bureau historical HU enumerations, revealing accuracies from 80 to 91% across the conterminous US (Theobald 2005). The ICLUS group used the SERGoM model and methods to approximate potential future changes in HU counts and developed land from 2000 to 2100. The SERGoM baseline US Census Bureau county population growth rates, travel time to urban centers (business districts), and household (family size) size were adjusted by the ICLUS group to correspond with the Special Report Emission Scenario (SRES) A1, B1, A2, and B2 storylines (EPA 2009; Bierwagen et al. 2010). For this study, we focus on the SRES A2 storyline because it represents the "high-end" emissions and most aggressive future HU SRES growth storyline.

2.2 Tornado Impact Monte Carlo model

The Tornado Impact Monte Carlo (TorMC) model simulates tornado events and estimates their impact or cost on an underlying cost surface (Strader et al. 2016a). TorMC model methods, components, and options are explicitly outlined in Strader et al. (2016a). The TorMC is used to simulate 10,000 years of significant tornado footprints (i.e., path length multiplied by path width; theoretical maximum extent of tornadic winds) across the study domain (Fig. 1). The domain was chosen because it represents the area with the highest frequency of tornadoes in the United States (Brooks et al. 2003a; Brooks et al. 2003b; Gagan et al. 2010; Dixon et al. 2011; Gensini and Ashley 2011; Marsh and Brooks 2012; Dixon and Moore 2012; Tippett et al. 2015). The domain contains three distinct subregions (i.e., Central Plains, Midwest, and Southeast) with differing tornado risk and exposure characteristics that have been investigated in prior works (Ashley and Strader 2016; Strader et al. 2016b). Each of the domains contains some of the most populated cities in the US, including Chicago, IL, Dallas-Fort Worth, TX, Atlanta, GA, St. Louis, MO, which can all locally elevate tornado impact likelihood and disaster potential.

Significant tornadoes were utilized since they have been responsible for most tornado fatalities and reported damage since 1950 (Ashley 2007; Simmons and Sutter 2011), and their counts have been relatively stable over the last 60 years (Verbout et al. 2006; Brooks et al. 2003a; Doswell 2007; Agee and Childs 2014; Ashley and Strader 2016). Simulated tornado footprint width was determined by Weibull distribution parameters associated with tornado intensity or magnitude (Brooks 2004). Simulated tornado path lengths, azimuths, and intensity ratings were selected by using a bootstrap, random selection with replacement technique on the historical tornado paths from 1954 to 2015 within the research domain. The TorMC model also ingests a weighting surface that controls simulated significant tornado initiation locations throughout the region (see Fig. 1 in Strader et al. 2016a). Lastly, the TorMC assesses simulated tornado costs using an "intersect" cost-extraction method (see Fig. 4 in Strader et al. 2016a) in conjunction with the underlying HU surface. This cost-extraction method ensures all HU grid cells intersecting a tornado footprint are included in tornado footprint cost estimation.

2.3 Future risk and exposure experiments

To provide a baseline assessment and representation of current tornado risk and exposure, a control risk surface was generated by taking historical (1954–2015) significant tornado events and mapping their frequency on an 80 km fishnet grid within the research domain (Fig. 1d). A gridded spatial resolution of 80 km was chosen because it represents the Storm Prediction Center's defined probability of severe weather within 25 miles of a given location (Brooks et al. 2003a). Due to the relatively short observed tornado record (<65 years), a low-pass filter was applied to the significant tornado frequency grid to provide a representative climatology of significant tornadoes for the region. The TorMC model employs this baseline risk surface to climatologically influence the simulation of 10,000 years of significant tornadoes and their impacts on the underlying 2010 HU exposure surface. Results from the control risk-exposure surface simulation are gathered in the form of annual tornado impact descriptive statistics (mean, median, standard deviation, 95th percentile, and 99th percentile) as well as a probability of exceedance (POE) curve (Strader et al. 2016a).

First, a baseline, or control, scenario is generated by combining risk derived from historically observed tornado events and exposure from the 2010 HU data (Fig. 1). The TorMC model is used to simulate 10,000 years of tornado events and their associated costs using the baseline control scenario risk and exposure variables. Tornado impact statistics from this simulation are compared with those from the future risk-exposure scenarios to assess how future tornado disaster probability might be altered in the twenty-first century.

The second step in the pragmatic experimental approach is to adjust the baseline tornado risk landscape as a means of exploring future tornado risk in the US. Although to date, no study has directly assessed future changes in tornado risk, many studies (Trapp et al. 2007; Brooks et al. 2014; Diffenbaugh et al. 2013; Gensini and Mote 2014; Tippett et al. 2015; Kim Hoogewind and Jeff Trapp, personal communication) have examined potential future changes in severe weather environments that are supportive of tornado development. For example, Trapp et al. (2007) and Diffenbaugh et al. (2013) have illustrated that the number of days with severe weather may increase up to 100% for locations within the Southeast by 2100 during the historically active tornado months of March, April, and May (Brooks et al. 2003a). Further, Gensini and Mote (2014) highlighted similar future changes using climate model downscaling and hazardous convective weather proxy report techniques. In general, the studies all indicate that the number of severe weather days and severe weather events are expected to rise largely due to increasing convective available potential energy (CAPE). Thus, this study assumes that annual tornado frequency and variability may also increase during the twenty-first century (Trapp and Hoogewind 2016; Kim Hoogewind and Jeff Trapp, personal communication).

Specifically, the TorMC simulations are modified by employing prior research findings (Trapp et al. 2007; Brooks et al. 2014; Diffenbaugh et al. 2013; Gensini and Mote 2014; Tippett et al. 2015; Kim Hoogewind and Jeff Trapp, personal communication) in two ways: (1) increasing the mean annual number of significant tornadoes to simulate and (2) escalating significant tornado occurrence annual variability. The mean annual frequency and variability of significant tornado events simulated in each TorMC run are increased by 50% (percentages supported by the findings in the aforementioned research) to examine how a "high-end" future tornado risk escalation may influence tornado impacts. The altered tornado risk surface is then used in conjunction with the 2010 HU surface and the TorMC model to estimate the relative influence of changing tornado risk on future disaster potential.

The third portion of the experimental control methodology assumes no changes in future tornado risk while allowing the underlying residential built environment to grow and expand. We hold constant the tornado risk from the baseline step and simulate 10,000 years of significant tornadoes and their estimated HU impact on the 2100 (A2) HU landscape. This process isolates the influence of changing societal exposure on twenty-first century tornado impact probability and disaster potential within the study domain.

Lastly, we allow both risk and exposure to change, producing an outcome that is likely more representative of disaster potential in the future. This approach captures both the influence of future changes in tornado risk and societal exposure on tornado impact potential. Although the exact cause is unknown, recent research (Brooks et al. 2014; Tippett et al. 2016) has illustrated that annual tornado occurrence variability has been increasing over the last few decades. As such, three future risk scenarios are combined with the 2100 (A2) HU landscape to assess the relative consequences of increasing significant tornado frequency with or without additional changes in annual tornado occurrence variability. The first simulation represents a 50% increase in annual tornado frequency *and* variability based on previous research findings (e.g., Trapp et al. 2007; Brooks et al. 2014; Diffenbaugh et al. 2013; Gensini and Mote 2014; Tippett et al. 2015; Kim Hoogewind and Jeff Trapp, personal communication). The second and third simulations denote 25 and 50% increases in significant tornado frequency with no twenty-first century change in annual tornado occurrence variability.

3 Results

3.1 Baseline control scenario

Baseline simulation results indicate that the expected median and mean annual number of HUs affected by significant tornadoes in the domain is 9330 HUs and 11,416 HUs, respectively, while the standard deviation is 8214 HUs (Table 1; Fig. 2). The 95th and 99th percentile of annual HU impacts represent high-end impact magnitudes that would likely represent an extremely devastating year with multiple tornado disasters. The baseline scenario produces 95th and 99th annual HU impact magnitudes of 26,490 HUs and 41,023 HUs, respectively, suggesting that in 2010 there was a 5% chance that as many as 26,500 homes could be affected by significant tornadoes. Annual HU impact threshold statistics (Table 2) illustrate that there is an 81% chance that greater than 5000 HUs and 0.7% chance that greater than 75,000 HUs could be damaged in a given 2010 baseline control simulation year. At the individual tornado scale, there is also a 20 and 0.97% chance that a single tornado in a given 2010 simulation year will affect at least 50 HUs or 5000 HUs, respectively (Table 3). It should be noted that HU impact magnitudes are subject to systematic error that results in the overestimation of HU impact estimation. This exaggeration can be attributed to the tornado cost-extraction method used (Strader et al. 2016a), the SERGoM-ICLUS modeled HU density computational and spatial limitations (Theobald 2005; EPA 2009), and the tornado footprint representation of a

Table 1 Study region annual tornado impact statistics (number of housing units) by simulation scenario

Simulation scenario	Median	Mean	Std. Dev.	95th percentile	99th percentile
Baseline control	9330	11,416	8214	26,490	41,023
Changing risk (+50%); constant exposure (2010 HU)	14,488	17,292	11,387	38,591	55,785
Changing exposure (2100 HU); constant risk (2010 HU)	15,847	20,571	16,614	52,006	82,731
Changing risk (+50%); changing exposure (2100 HU)	25,311	31,200	22,584	73,037	108,821
Changing risk (+25% (no var chng)); changing exposure (2100 HU)	20,641	25,713	19,651	61,472	92,380
Changing risk (+50% (no var chng)); changing exposure (2100 HU)	25,778	31,218	22,195	72,677	109,287

tornado path (i.e., a theoretical tornado footprint (length × width)) that may overestimate actual tornado damage paths by up to 50% (Strader et al. 2016a). Thus, the study stresses the importance of *relative* differences between HU impact statistics for each of the tornado risk-exposure scenarios.

3.2 Changing risk-constant exposure scenario

Results from the changing risk-constant exposure and changing exposure-constant risk scenarios provide insight about the relative effects of risk and exposure on future 2100 HU impact and disaster probability. Again, this scenario represents a case where HU growth is abruptly stopped in 2010 and remains constant for the next 90 years (2010–2100), while climatological factors increases tornado risk. Compared to the baseline simulation results, the changing risk-constant exposure scenario yields increased median, mean, standard deviation, and 95th and 99th percentile HU impact statistics (Table 1; Fig. 2). Because of increased risk, median and mean annual tornado impact magnitudes are 55% (5158 HUs) and 52% (5876 HUs) greater than the baseline.

Changing risk-constant exposure tornado impact standard deviation is also 3173 HUs larger than the baseline control indicating a rise in HU impact variability. The 95th and 99th

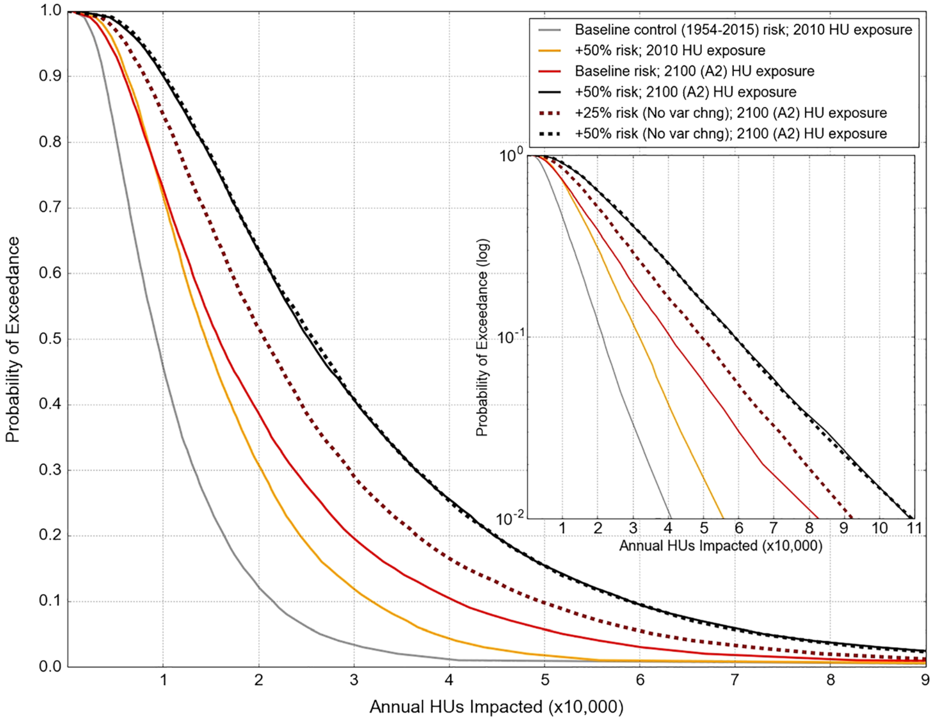

Fig. 2 Baseline (*gray dashed*), changing risk (+50% increase) and constant 2010 HU exposure (*orange*), changing (2100 A2) exposure and constant risk (*red*), changing risk (+50% frequency and variability) and changing (2100 A2) exposure (*black*), changing risk (+25% frequency and no change in annual variability) and changing (2100 A2) exposure (*dashed dark red*), and changing risk (+50% frequency and no change in annual variability) and changing (2100 A2) exposure (*dashed black*) probability of exceedance (POE) curves for the study domain

percentile HU impact magnitudes for the changing risk-constant exposure scenario are also increased to 46% (12,101 HUs) and 36% (14,762 HUs) due amplified risk. Increasing the frequency of significant tornadoes in the future has a much more profound effect on disaster potential compared to increasing the annual variability. No major differences in tornado impact statistics associated with escalating annual tornado frequency variability by 100 or 50% were discovered.The changing risk-constant exposure tornado impact threshold statistics also suggest that there will be an increase annual HU impact threshold magnitude (Tables 2 and 3). This outcome was expected due to the combination of *annual* increases in tornado risk and the use of the 2010 HU surface to estimate tornado costs. Annual HU impact threshold statistics are expected to be from 14% (75,000 HU impact threshold) to 210% (25,000 HU impact threshold) greater than the baseline scenario.

3.3 Changing exposure-constant risk scenario

Holding constant tornado risk and allowing exposure to increase from 2010 to 2100 (Special Report Emission Scenario A2) also leads to greater future HU impact magnitudes. The median, mean, and standard deviation tornado impact magnitudes for the changing exposure-constant risk scenario are 70% (6517 HUs), 80% (9155 HU), and 102% (8400 HUs) greater than the baseline statistics. Changing exposure-constant risk 95th and 99th percentile annual HU impacts are approximately two times greater than the baseline scenario. This doubling of disaster potential is attributed to the projected growth in HUs within the domain from 2010 to 2100. Over the 90-year period, the total number of HUs in the domain is projected to increase 28.6 million with urban, suburban, and exurban land use footprints enlarging 10,329, 23,088, and 12,112 km^2, respectively (Table 4). Again, annual HU impact threshold statistics illustrate that increasing twenty-first century exposure may lead to greater annual tornado impact potential, especially for high-end (i.e., 25,000 HUs, 50,000 HUs, and 75,000 HUs) magnitudes. At the individual tornado scale, changing exposure-constant risk HU impact thresholds are projected to increase as much as 75% for the 5000 HU impact threshold (Table 3). An individual tornado impact magnitude of 5000 HUs is 1.4 times the number of HUs damaged in the 2011 Newcastle-Moore, OK EF5 tornado (Atkins et al. 2014).

Comparing the changing risk-constant exposure and changing exposure-constant risk scenario results suggests that increasing societal exposure will have a greater influence on future tornado impact magnitude and disaster potential compared to potential climate change

Table 2 Annual tornado impact magnitude probabilities for the region by simulation scenario. Housing unit (HU) magnitude impact threshold probabilities of 5000, 10,000, 25,000, 50,000, and 75,000 are provided

Simulation scenario	Threshold (annual no. HUs affected)				
	5000	10,000	25,000	50,000	75,000
Baseline control	0.813	0.458	0.061	0.009	0.007
Changing risk (+50%); constant exposure (2010 HU)	0.948	0.718	0.189	0.017	0.008
Changing exposure (2100 HU); constant risk (2010 HU)	0.933	0.730	0.277	0.057	0.014
Changing risk (+50%); changing exposure (2100 HU)	0.984	0.900	0.506	0.154	0.046
Changing risk (+25% (no var chng)); changing exposure (2100 HU)	0.971	0.843	0.388	0.097	0.025
Changing risk (+50% (no var chng)); changing exposure (2100 HU)	0.987	0.905	0.516	0.154	0.045

Table 3 Individual simulated tornado impact magnitude probabilities for the region by simulation scenario. Housing unit (HU) magnitude impact threshold probabilities of 50, 100, 250, 500, 1000, and 5000 are provided

Simulation scenario	Threshold (no. HUs affected)					
	50	100	250	500	1000	5000
Baseline control	0.2071	0.1381	0.0719	0.0395	0.0196	0.0097
Changing risk (+50%); constant exposure (2010 HU)	0.2075	0.1380	0.0721	0.0395	0.0195	0.0097
Changing exposure (2100 HU); constant risk (2010 HU)	0.2291	0.1602	0.0932	0.0580	0.0343	0.0099
Changing risk (+50%); changing exposure (2100 HU)	0.2288	0.1602	0.0933	0.0579	0.0342	0.0100
Changing risk (+25% (no var chng)); changing exposure (2100 HU)	0.2289	0.1601	0.0936	0.0584	0.0345	0.0099
Changing risk (+50% (no var chng)); changing exposure (2100 HU)	0.2292	0.1607	0.0938	0.0584	0.0347	0.0100

driven alterations in tornado risk. Although *both* changes in tornado risk and exposure lead to increased HU impacts in the future, the difference between the baseline tornado impact magnitudes and the changing exposure scenario results is much larger. For instance, median and 95th percentile changing exposure-constant risk annual HU impact values are 10 and 35% greater, respectively, than those associated with the changing risk-constant exposure scenario (Table 1).

Probability of exceedance or POE curves provide insight into the differences in future risk and exposure as it pertains to tornado disaster potential (Fig. 2). For example, the greater spacing, especially from POE = 0.5 to POE = 0.05, between the baseline and the changing risk-constant exposure scenarios highlights how the influence of changing exposure may have a greater effect on future HU impacts and disaster potential. POE curve shape differences between the constant risk and constant exposure scenarios illustrate that the effects of solely increasing risk are much more apparent for low-end (POE < 0.7) annual tornado impact magnitudes. Only greater than POE = 0.7 does the changing exposure-constant risk curve begin to separate from the changing risk-constant exposure curve (Fig. 2). Because twenty-first century changes in exposure comprise both elements of an increasing total number of HUs and escalating developed land area (i.e., sprawl), we surmise that the majority of the difference between changing risk and changing exposure curves from POE < 0.7 to POE > 0.05 is due to the effects of sprawl, or "spreading out," of HUs across geographic space from 2010 to 2100.

Table 4 Total number of housing units (HUs) in 2010 and 2100 (A2), total developed land area (km^2) by urban, suburban, exurban, and rural land use classification, and the absolute and percentage change in HUs or land use area from 2010 to 2100

		Land use area (km^2)			
Exposure surface and statistics	HU count	Urban	Suburb.	Exurb.	Rural
2010	35,510,072	6038	37,670	416,657	1,294,262
2100 A2	64,101,221	16,367	60,758	428,769	1,248,733
Absolute change (HU)	28,591,149	10,329	23,088	12,112	−45,529
Percentage change (%)	80.52	171.06	61.29	2.91	−3.52

3.4 Changing risk and exposure scenario

A more probable future scenario is that both environmental and societal changes will act together to alter tornado disaster probability (Fig. 2). Increasing annual tornado frequency and occurrence variability by 50% and estimating HU impacts using the 2100 (A2) HU exposure surface yields a 170% escalation in the median and mean annual HUs affected (Table 1). Moreover, annual tornado impact variability could be as much as 2.75 times higher by 2100. The 95th and 99th percentile are also projected to increase 176 and 165%, respectively, by 2100. In addition, annual HU impact thresholds of 25,000 HUs, 50,000 HUs, and 75,000 HUs are all expected to be at least 6.5 times more probable in 2100 than 2010. When increasing future tornado annual frequency *and* occurrence variability 1.5 times, individual HU impact threshold statistics are nearly identical to the changing exposure-constant risk threshold probabilities because both scenarios employ the 2100 (A2) exposure surface.

Changing future tornado risk by increasing solely the annual tornado frequency 50% and holding constant the annual occurrence variability yields comparable tornado impact statistics and disaster potential to that of inflating *both* future tornado frequency and variability 50%. For example, the probability that 10,000 homes are damaged in 2100 is 0.91 when inflating solely future tornado frequency 1.5 times and 0.90 when escalating both tornado frequency and variability 50% (Table 2). These similar results indicate that increasing annual tornado occurrence variability will not have as strong of an influence on future tornado disaster potential as an amplifying twenty-first century tornado frequency (Tables 1, 2, and 3; Fig. 2). Employing the 2100 (A2) exposure surface and increasing future tornado frequency 25% without any changes to annual occurrence variability yields an approximate 25% lower disaster potential than increasing future tornado risk by 50%; this suggests that impact changes found in additional TorMC simulations modifying climatological risk would be proportional to prescribed risk modification of each simulation (Tables 1, 2, and 3; Fig. 2).

4 Discussion and conclusions

This study employed a pragmatic experimental control methodology in conjunction with projected tornado risk and demographic data to assess the relative contributions of each disaster constituent on future tornado impacts. Using Monte Carlo simulations that considered both tornado risk and societal exposure, the research revealed that changes in societal exposure *may* be more important than changes in climatological risk in fostering future tornado disaster potential. Nevertheless, the combination of increasing tornado risk and exposure surpasses the effects of changes solely in tornado risk or exposure during the twenty-first century. Results illustrate that locations in high-risk tornado regions (e.g., Atlanta, GA; Chicago, IL; Dallas-Fort Worth, TX; St. Louis, MO) may experience increased disaster probability in the future. Moreover, historically vulnerable regions—such as the southeastern US—may be at greater risk of tornado disaster due to the combined effects of increasing tornado risk (Trapp et al. 2007; Brooks et al. 2014; Diffenbaugh et al. 2013; Gensini and Mote 2014; Tippett et al. 2015), rapidly amplifying exposure (Ashley and Strader 2016), and a complex tapestry of preexisting social and physical vulnerabilities (Ashley 2007; Ashley et al. 2008; Simmons and Sutter 2011).

Findings presented in this study highlight how tornado risk and societal exposure may potentially lead to greater tornado disaster probability in the future. Regions and communities in at-risk locations in the US should take proactive measures to help combat the effects of increasing tornado disaster potential. Disaster mitigation strategies that attempt to make communities more resilient by taking tornado risk and exposure into account will ultimately become more important as the consequences of increased risk and exposure are realized in the future. Building of storm shelters or safe rooms (Merrell et al. 2002; Paton and Johnston 2006; Simmons and Sutter 2007; Prevatt et al. 2012; Simmons et al. 2015), improved hazard risk communication and warning dissemination systems (e.g., Wacinger et al. 2013), the retrofitting of existing structures so they are more resilient, the adoption of new and enforcement of existing building codes (Prevatt et al. 2012; Simmons et al. 2015), and the potential consideration and/or implementation of new zoning policies that consider tornado hazard risk (Godschalk et al. 1998; Burby 2003; Pearce 2003; Mann 2014; IPCC 2014) may act together to reduce the effects of future tornado events.

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