

Observed and Projected Changes in United States Tornado Exposure[✉]

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ABSTRACT

This study examines how tornado risk and societal exposure interact to create tornado disaster potential in the United States. Finescale historical and projected demographic data are used in a set of region-specific Monte Carlo tornado simulations to reveal how societal development has shaped, and will continue to shape, tornado disaster frequency and consequences. Results illustrate that although the U.S. Midwest contains the greatest built-environment exposure and the central plains experience the most significant tornadoes, the midsouth contains the greatest tornado disaster potential. This finding is attributed to the relatively elevated tornado risk and accelerated growth in developed land area that characterizes the midsouth region. Disaster potential is projected to amplify in the United States due to increasing built-environment development and its spatial footprint in at-risk regions. In the four regions examined, both average annual tornado impacts and associated impact variability are projected to be as much as 6 to 36 times greater in 2100 than 1940. Extreme annual tornado impacts for all at-risk regions are also projected to nearly double during the twenty-first century, signifying the potential for greater tornado disaster potential in the future. The key lesson is that it is the juxtaposition of both risk and societal exposure that drive disaster potential. Mitigation efforts should evaluate changes in tornado hazard risk and societal exposure in light of land-use planning, building codes, and warning dissemination strategies in order to reduce the effects of tornadoes and other environmental hazards.

1. Introduction

Increasing trends in weather-related disasters and losses are a function of climate and society (Changnon et al. 2000; Bouwer 2011; IPCC 2012). Much of the research investigating the amplification in disaster consequences has focused on possible changes in hazard risk resulting from anthropogenic climate change [Peterson et al. 2013; Kunkel et al. 2013; National Academies of Science Engineering and Medicine 2016]. While hazard risk is an important component of disasters, the sustained increase in hazard consequences is thought to be driven principally by the growth in underlying human

and built-environment vulnerabilities and increasing wealth (Pielke 2005; Hölpe and Pielke 2006; Bouwer 2011; IPCC 2012; Preston 2013; IPCC 2014; Mohleji and Pielke 2014; Ashley et al. 2014; Strader and Ashley 2015).

Many studies have focused on the spatiotemporal characteristics of tornado risk and/or vulnerability (Brooks et al. 2003a; Dixon et al. 2011; Ashley et al. 2014; etc.). Early research (Finley 1887; Wolford 1960; Thom 1963) on tornado risk was created without regard to tornado intensity and seasonality (Brooks et al. 2003a), but, in the 1970s and 1980s, major changes in tornado climatology research—such as the inclusion of damage magnitude and spatial attributes of paths—permitted a broader assessment of tornado characteristics and their climate (e.g., Abbey and Fujita 1975, 1979; Fujita 1981; Schaefer et al. 1986). More recent research (e.g., Brooks et al. 2003a; Dixon et al. 2011; Elsner et al. 2014; Brooks et al. 2014; Farney and Dixon 2015) analyzing tornado risk has used *Storm Data*, which is a

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database developed by the National Climatic Data Center and the National Weather Service that contains attribute information on pathlength, width, and the maximum damage rating for every tornado segment within a county (Edwards et al. 2013). These studies have examined a spectrum of tornado risk attributes such as tornado occurrence (Brooks et al. 2003a; Dixon et al. 2011; Elsner et al. 2014), economic impact (Daneshvaran and Morden 2007; Simmons et al. 2013), and daily or seasonal timing (Brooks et al. 2003a; Dixon et al. 2011).

Additional research (e.g., Rae and Stefkovich 2000; Wurman et al. 2007; Hall and Ashley 2008; Paulikas and Ashley 2011; Ashley et al. 2014; Rosencrants and Ashley 2015; Ashley and Strader 2016) has focused on societal exposure to tornadoes (hereafter, tornado exposure) rather than tornado risk. These studies often use enumerations of people and/or the built environment (number of homes, structures, etc.) to evaluate the potential effects of a tornado hazard. Results from these studies demonstrate that ever-increasing population growth leads to the more frequent placement of people and their assets in harm's way (Changnon and Burroughs 2003; Wilson and Fischetti 2010; Paulikas and Ashley 2011; Burkett and Davidson 2012; Ashley et al. 2014; Ashley and Strader 2016). Because of advancements in computing technology and software, methodologies and models have been developed to estimate potential impacts and losses from tornadoes in populated locations (Rae and Stefkovich 2000; Wurman et al. 2007; Ashley et al. 2014; Strader et al. 2016). Using geographic information systems (GIS), these studies often place highly detailed, damage-surveyed tornado paths or their likeness (e.g., Wurman et al. 2007; Ashley et al. 2014; Strader et al. 2015, 2016) atop developed areas to estimate potential hazard effects and disaster potential. Additional research has attempted to measure the change in tornado exposure through time using a variety of statistical and spatial techniques (Hall and Ashley 2008; Paulikas and Ashley 2011; Ashley et al. 2014; Ashley and Strader 2016; Strader et al. 2016). To date, only a handful of studies have examined changes in future tornado risk (Trapp et al. 2007, 2011; Diffenbaugh et al. 2013; Robinson et al. 2013; Gensini and Mote 2015; Trapp and Hoogewind 2016) or exposure (Preston 2013; Rosencrants and Ashley 2015), employing a variety of projected climate, environmental, population, and socioeconomic data.

In this investigation, we seek to further research on U.S. tornado exposure by evaluating how human development has augmented disaster potential and, moreover, how projected changes in housing units (HUs) and developed land area may influence disaster frequency

and consequences in the future. Although disasters are social phenomena and largely driven by extreme events interacting with human, social, and physical vulnerabilities, the study defines disaster potential as a quantitative measure of the number of HUs potentially damaged or destroyed by a tornado (Ashley and Strader 2016; Strader et al. 2016). The study makes the assumption that the greater the number of homes potentially affected by a tornado, the greater the tornado disaster probability and magnitude.

The tornado hazard and regional tornado risk are used in conjunction with historical and projected built-environment data in a new statistical resampling framework to assess changing disaster potential. Because many terms (risk, vulnerability, etc.) in hazard science contain a multitude of designations and meanings (Paul 2011), we employ the basic climatological definition of risk that represents the probability of a hazard occurring in space and time with varying characteristics (tornado width, length, magnitude, direction, etc.). This study also focuses on residential built-environment (i.e., HU) exposure. Vulnerability is multifaceted and often includes physical and human exposure elements (e.g., built environment, population, and other demographics), adaptive capacities (i.e., how an entity copes or adapts to a hazard), and sensitivities (i.e., the degree to which an entity is affected by a hazard; Cutter et al. 2009; Morss et al. 2011). While the focal point of this study is narrow within a complex, multilayered vulnerability framework, residential built-environment data provide a tangible and robust marker for assessing how societal development has evolved and will evolve in areas prone to tornadoes.

2. Data and methodology

a. Spatially Explicit Regional Growth Model data

Previous studies have primarily used U.S. decennial census data to investigate tornado exposure (e.g., Wurman et al. 2007; Hall and Ashley 2008; Ashley et al. 2014). Because U.S. decennial census' geographical units of aggregation vary from one census to another at fine spatial scales (e.g., block-level data; Cai et al. 2006), results from previous investigations have been temporally and spatially restricted. However, these issues have been addressed and controlled for by the Spatially Explicit Regional Growth Model (SERGoM; Theobald 2005). The SERGoM model produces gridded, decadal, finescale (100-m resolution) historical HU density estimates across the conterminous United States. Model accuracy was measured by employing a hindcast technique in conjunction with U.S. Census Bureau historical population and HU metrics (Theobald 2005). Cross-validation results

between the hindcast and U.S. Census Bureau metrics indicated that SERGoM HU estimations performed well with accuracies ranging from 80% to 91% (Theobald 2005).

b. Integrated Climate and Land-Use Scenarios and Special Report Emissions Scenarios data

More recently, the Integrated Climate and Land-Use Scenarios (ICLUS) research group has coupled the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) A1, A2, B1, and B2 projections with the SERGoM model to estimate future HU density and population (Bierwagen et al. 2010). The ICLUS group modified HU projections by varying the SERGoM baseline county population growth rates, household size (i.e., the number of people in a single HU), and travel time to urban centers by the four primary SRES storylines (EPA 2009; Bierwagen et al. 2010). The A1 storyline comprises rapid economic development, low population growth, and global integration. Housing growth rates in the A1 SRES are limited due to low fertility and smaller household size (EPA 2009). The A2 SRES scenario is the most aggressive HU and population projection where steadily increasing development rates drive twenty-first-century economic regional growth. The B1 scenario is similar to the A1 storyline but with a greater emphasis on the environment and sustainable economic growth with slowly decreasing growth rates. The B2 storyline illustrates a regionally oriented landscape with moderate population growth as well as a focus on local solutions to environment and economic issues and consistent growth rates. A fifth, base case (BC), scenario sets all model parameters (travel time, migration, etc.) to medium. The study places an emphasis on the A2 and BC SRES storylines because the A2 represents a worst-case projection and the BC highlights a “middle-of-the-road” HU growth scenario.

Our research utilizes the HU as the principal measure of residential tornado exposure because it is the primary underlying metric derived in the SERGoM-ICLUS model. Additionally, the HU provides a reasonable measure of tornado exposure given that HU counts are temporally more stable than population counts (Theobald 2005), and more than 75% of all tornado deaths (2003–15) occur in residential housing (Ashley and Strader 2016).

c. Tornado Impact Monte Carlo model

Properly examining tornado exposure is often problematic because of small sample size (i.e., approximately 65 yr of observed tornado data), data inaccuracy and bias, and relatively rare event occurrence in the

observed tornado record (Brooks et al. 2003a; Doswell 2007). In addition, historical extremes in tornado characteristics (length, width, counts, etc.) may not have been observed, or sampled, during the last 65 yr of recorded data (Meyer et al. 2002; Doswell 2007; Strader et al. 2016). Nonetheless, a potential solution, or control for some of these issues, is to utilize Monte Carlo simulation. Monte Carlo simulation is a numerical modeling method that utilizes repeated random sampling to obtain the distribution of an unknown probabilistic entity (Mooney 1997). Monte Carlo simulation comprises two unique attributes: iteration and randomness. These two characteristics allow Monte Carlo simulations to provide probabilistic solutions about likely best-case and worst-case outcomes. Monte Carlo simulation yields a larger “window” of tornado event outcomes based on the historically observed tornado data (Meyer et al. 2002; Strader et al. 2016). This study employs the Tornado Impact Monte Carlo (TorMC) model (Strader et al. 2016), which can simulate thousands of tornado paths and estimate their potential impacts on an underlying HU cost surface. For this particular research, we define HU or tornado “impact” as the sum number of housing units that a simulated tornado intersects. Specifically, the individual conterminous U.S. SERGoM-ICLUS HU decadal surfaces from 1940 to 2100 are used in conjunction with the spatially explicit TorMC model to estimate changes in tornado impact potential and exposure from 1940 to 2100 for all scenarios in equal-area, at-risk tornado regions in the United States (central plains, high plains, midsouth, and Midwest; Fig. 1). Two of these regions, the central plains and high plains, were chosen because they are geographically positioned in an area that contains some of the highest mesocyclone supportive environments and tornado frequencies in the world (cf. Brooks et al. 2003a; Gagan et al. 2010; Dixon et al. 2011; Marsh and Brooks 2012; Dixon and Mercer 2012; Smith et al. 2012; Tippett et al. 2015). In addition, the central and high plains domains are characterized as largely rural landscapes with few highly developed urban areas. The midsouth was selected because it represents an area that contains a relatively high tornado frequency (Ashley 2007; Coleman and Dixon 2014; Ashley and Strader 2016) intersecting a comparatively developed landscape and, in addition, is an area that has high tornado vulnerability and mortality (Ashley 2007; Ashley and Strader 2016). Last, the Midwest domain was chosen because it signifies a geographic region that is highly populated but contains a slightly lower tornado frequency compared to the other three regions. Overall, by examining alterations in tornado impact metrics from each simulation over time and across geographic space,

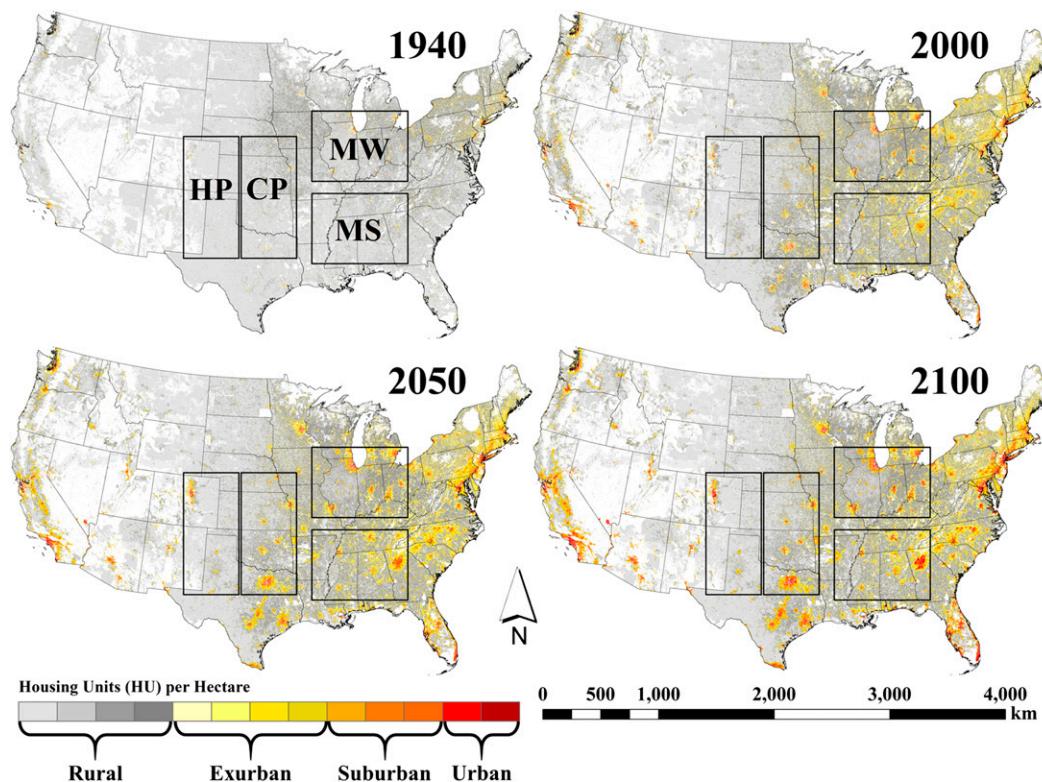


FIG. 1. The total number of HU per hectare for 1940, 2000, 2050 (using A2 SRES scenario), and 2100 (A2) for the central plains (CP), high plains (HP), midsouth (MS), and Midwest (MW) with color denoting land-use classification defined as rural ($>16.18 \text{ ha HU}^{-1}$), exurban ($0.68\text{--}16.18 \text{ ha HU}^{-1}$), suburban ($0.1\text{--}0.68 \text{ ha HU}^{-1}$), and urban ($<0.1 \text{ ha HU}^{-1}$; after Theobald (2005)).

changes in tornado exposure and disaster potential for the regions can be approximated.

A detailed description of the TorMC model methods, steps, and verification is discussed in Strader et al. (2016) and summarized in Table S1. In general, the TorMC model encompasses four steps: 1) study region and model parameter definition, 2) tornado footprint generation, 3) tornado path cost calculation, and 4) output production (Strader et al. 2016). For this specific examination, the TorMC model was used to simulate 10000 replicate years of significant—that is, EF2 or greater magnitude—tornado footprints (i.e., tornado pathlength by path width, which represents the hypothetical maximum extent of tornadic winds) within each study region. The simulation epoch of 10000 replicate years represents a trade-off of computational efficiency with precision (distributional smoothness) in modeled output. Significant tornadoes were selected because they have been responsible for 99% of all tornado fatalities and 75% of the reported damage since 1950 (Ashley 2007; Simmons and Sutter 2011). Moreover, significant tornado frequency has remained relatively consistent since 1950, while nonsignificant annual tornado

frequency continues to increase due to non-meteorological influences (e.g., population-influenced reporting biases; Verbout et al. 2006; Brooks et al. 2003a; Doswell 2007).

The TorMC model requires some additional parameter choices prior to simulation (Strader et al. 2016). For this study, only those historical observed tornado counts from 1954 to 2014 in each corresponding region are sampled due to the underreporting of tornadoes prior to the establishment of National Severe Storms Forecast Center in the early part of the 1950s (Agee and Childs 2014). Weibull parameters from Brooks (2004) are used to simulate significant tornado widths by EF-scale magnitude, while lengths, azimuths, and magnitudes are selected using a bootstrap, or random sampling with replacement, technique on each region's observed historical tornado data from 1954 to 2014.

This study uses the TorMC's random tornado touchdown probability method to determine tornado placement and costs. The random tornado touchdown method ensures that the tornado starting point likelihood or probability is equal for all locations within the simulation study region [see Fig. 5b in Strader et al. (2016)].

Although this random tornado touchdown technique removes any potential climatological and/or environmental patterns in regional tornado occurrence, it does help avoid population density–induced reporting bias often found in historical tornado data (e.g., Grazulis 1993; Brooks et al. 2003a; Doswell et al. 2005; Elsner et al. 2013; Strader et al. 2015). Once 10 000 replicate years of significant tornado footprints have been simulated atop the region of interest, the TorMC model assesses each tornado footprint’s HU impact on the underlying HU cost surface. An “intersect” cost-extraction technique was employed to calculate tornado–HU impacts by including all cost surface grid cells that are intersected by simulated tornado footprints [see Fig. 4 in Strader et al. (2016)]. The TorMC model output provides the unique tornado field identifier (FID), footprint polygon geometry, starting latitude and longitude, ending latitude and longitude, pathlength (km) and width (km), azimuth ($^{\circ}$), magnitude (0–5), simulation year, and HU impacts. Last, each simulated tornado–HU impact value is grouped by its simulation year and summed to provide a regional estimate of annual HU impacts by significant tornadoes. This method provides a robust approximation of regional tornado disaster potential and tornado exposure.

It should be noted that although recent studies have suggested that future severe weather environments may alter the spatiotemporal characteristics of tornadoes during the twenty-first century (Trapp et al. 2007; Diffenbaugh et al. 2013; Gensini and Mote 2015), this study assumes no future change in significant tornado risk in order to isolate the influence changing tornado exposure has on future tornado disaster potential.

d. Probability of exceedance and descriptive statistics

To illustrate changes in regional tornado exposure and disaster potential, we employ probability of exceedance (POE) curves and descriptive annual tornado impact statistics. In general, four primary descriptive metrics (median, mean, standard deviation, and 95th percentile) are employed to characterize changes in regional tornado exposure, disaster potential, and annual impact POE. Given the rare occurrence of tornadoes and associated disasters, POE curves and the impacts associated with tornado events resemble an extreme value distribution (Weibull, Gamma, etc.). While the mean is commonly used to highlight a distribution’s central tendency, the median serves as a standard measure of central tendency that is most useful when there are extreme outliers within the distribution. The standard deviation is used as a mechanism for determining annual tornado impact variability, and the 95th percentile of annual tornado impacts are used to

examine high-end tornado impact years and disaster potential. Last, the POE curve shape and scale provides a graphical representation of annual tornado impact statistics for each at-risk region. Relative differences in tornado impact descriptive statistics and POE curve characteristics capture changes in tornado exposure, estimated impacts, and disaster potential across spatiotemporal extents (Strader et al. 2016).

POE curves represent the total number of HUs impacted by significant tornadoes in a given simulation year for a particular SERGoM–ICLUS decadal cost surface ranging from 1940 to 2100 (by SRES and BC scenarios). The primary reason for generating annual HU impact POE curves per cost surface is to provide insight on how the distribution of HU impacts has changed and may change in the future based on a range of twenty-first century HU growth scenarios. This study considers historical time periods as the decades of 1940 through 2000 and projected time periods to be those years from 2010 to 2100. This approach was chosen because the ICLUS twenty-first century HU projection model was initialized with 2000 census and other physical attribute data (EPA 2009); thereafter, the ICLUS-modeled local growth rates, accessibility to urban centers, travel time, household size, and so on, were modified consistently with the SRES projections.

3. Results

a. Tornado impact measures of central tendency

Tornado impact measures of central tendency represent the expected regional total number of HUs affected by tornadoes in a given simulation year for a particular decadal cost surface. As expected, all at-risk U.S. regions are projected to undergo an increase in tornado exposure and impact potential in the future century (Table 1; Figs. 3, S1–S3). The midsouth has the greatest absolute and relative change in the number of HUs potentially impacted for a majority of the past (1940–2000) and future (2010–2100) periods (Table 1; Fig. 2c). From 1940 to 2000, the median number of midsouth HUs impacted by significant tornadoes per simulation year grew by 2185 HUs, or a 1543% increase, whereas across the entire 160-yr study period, median HU impacts are projected to increase by as much as 2867% under the A2 scenario (Table 1). Projected HU impacts in the midsouth are influenced largely by the A2 storyline’s high domestic migration from the northern United States to the midsouth (i.e., coastal area, mountainous areas, and warmer climates are attracting affluent and/or retired individuals; Manson and Groop 2000). This effect results in higher midsouth population growth rates and an overall greater change in the region’s HUs

TABLE 1. Absolute and percentage change in tornado impact descriptive statistics (median, mean, standard deviation, and 95th percentile) from 1940 to 2100 by region.

	Descriptive statistic	1940	2100 (A2)	Absolute change	% change
Central plains	Median	208.9	2742.4	2534	1213
	Mean	354.2	5314.6	4960	1400
	Std dev	515.0	8128.8	7614	1478
	95th percentile	1154.9	18 242.8	17 088	1480
High plains	Median	3.8	46.0	42	1101
	Mean	29.0	648.3	619	2139
	Std dev	158.2	2470.5	2312	1462
	95th percentile	107.1	2900.0	2793	2608
Midsouth	Median	141.7	4203.2	4062	2867
	Mean	233.4	7744.4	7511	3219
	Std dev	327.5	11 834.8	11 507	3514
	95th percentile	722.1	25 762.0	25 040	3468
Midwest	Median	355.0	3612.6	3258	918
	Mean	692.9	6092.4	5400	779
	Std dev	1137.1	7417.0	6280	552
	95th percentile	2392.6	20 507.8	18 115	757

throughout the twenty-first century compared to all other domains (Table 2). Contributing to this rapid change in tornado impacts are the notable losses in rural land area and corresponding growth in sprawling exurban and suburban land development morphologies that have characterized, and will continue to characterize, the midsouth.

The Midwest exemplifies the second greatest absolute change in estimated tornado impacts from 1940 to 2100 (Table 1). The Midwest's median (mean) annual number of HUs impacted is expected to increase as much as 918% (779%), or 3258 (5400) HUs, during the 160-yr study period (Table 1; Figs. 3a,b). A majority of the growth in Midwest HU impacts occurred during the historical portion of analysis where the median number of HUs affected by significant tornadoes inflated 493% (Fig. 3a). This rapid change in tornado impact potential is a result of enhanced population and HU growth that characterized the United States following World War II (i.e., "Baby Boom" and post-1940s suburbanization). Although the Midwest contains a greater number of large population centers and the central plains experience a greater frequency of significant (enhanced Fujita scale 2+ or EF2+) tornadoes per year on average compared to the midsouth, the collective midsouth median and mean impacts are projected to outpace the central plains and Midwest (Figs. 3a,b). This result is due to the midsouth's elevated tornado risk juxtaposed with high HU density and more rapid development. While differences in regional tornado risk play a role, the primary cause for the disparity between historical midsouth and Midwest tornado impacts can be attributed to changes in HU counts and land use (Tables 2 and 3). The Midwest is projected to add as many as 1.5 million more HUs than the midsouth during the 160-yr period, yet the

relative HU growth (3242%) in the midsouth is much larger than the Midwest (768%) for the same period (Table 3). In addition, the percentage of developable land in the Midwest classified as rural is projected to decrease as much as 27% by 2100, while in the midsouth rural land percentage is projected to be reduced by up to 33% (Table 2). During this same period, midsouth exurban land area is estimated to increase as much as 1488%, and Midwest exurban land is expected to increase as much as 457%. These changes indicate that the relatively higher conversion rates of rural land to exurban, suburban, and urban land use in the midsouth will lead to more substantial tornado impacts during the twenty-first century compared to the Midwest.

The central plains are expected to experience as much as a 1213% (1400%) change in median (mean) HU impacts during the 160-yr study period (Table 1; Figs. 2a,b, S1–S3). The difference between central plains and midsouth annual median and mean tornado impacts can be attributed, at least in part, to the contrasting HU growth rates in the central plains and midsouth. The central plains are projected to gain as many as 14.8 million HUs by 2100, acquiring 5.7 million fewer HUs than the midsouth (Table 3). This difference is a result of the lower (765%) projected central plains exurban growth from 1940 to 2100 compared to the midsouth (1488%; Table 2). Although the central plains and midsouth contained similar median and mean annual tornado impacts in 1940, by 2000 the midsouth median and mean impact values had inflated to 2327 and 3366 HUs, respectively, surpassing the central plains' impacts by nearly 160% (Table 1; Figs. 3a,b).

The high plains contain the lowest change in tornado impacts from 1940 to 2100 compared to all at-risk

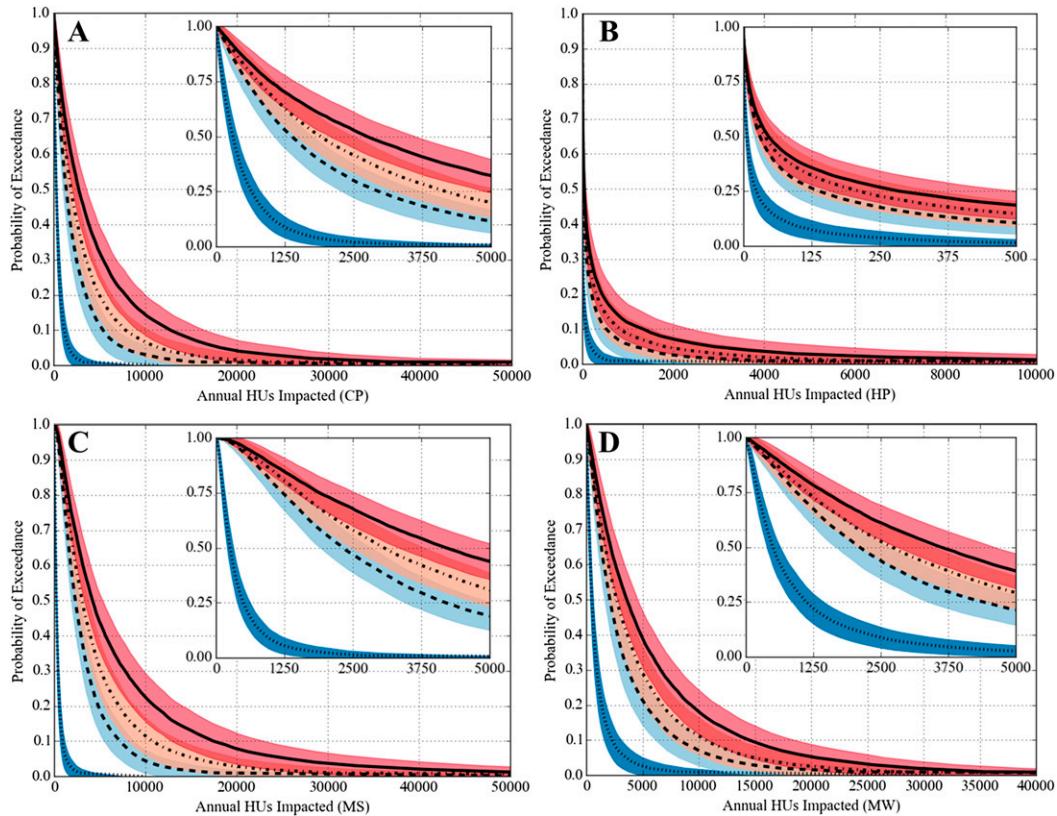


FIG. 2. POE curves representing the annual number of HU potentially affected by significant tornadoes in the (a) central plains, (b) high plains, (c) midsouth, and (d) Midwest for 1950 (dotted line), 2000 (dashed line), 2050 (dotted–dashed line; A2 SRES scenario), and 2100 (solid line; A2) decadal cost surfaces. The shaded envelopes represent the POE curve 95% confidence intervals. Breakout plots provide perspective on the POE curve's 50th percentile.

tornado regions. This finding is attributed to the vast amount of rural land (95% of total developable area) estimated to exist in the high plains through the remainder of the century and the presence of small, isolated communities that are not projected to experience much sprawl because of the lack of large population centers (Fig. 1). This more rural landscape results in a POE curve that decays much more quickly (Fig. 2) as well as lower tornado impact measures of central tendency.

b. Tornado impact variability

Tornado impact variability illustrates the expected year-to-year differences in the annual number of HUs affected by significant tornadoes for a specific region and decadal cost surface. Examining annual tornado HU impact variability, for each region from 1940 to 2100 reveals that the midsouth, by far, contains the greatest amount of variability (Table 1; Figs. 3c,g). However, during the historical period of analysis, the Midwest has the highest variability in annual tornado impacts due to

its large number of high HU density cities as well as substantial areas within the region containing low HU density (agricultural land, protected areas, etc.). For instance, although the Midwest is projected to have the greatest percentage of urban (1.4%) and suburban (4.9%) land compared to the other at-risk tornado regions by 2100 under the A2 scenario, it is also projected to contain a higher percentage of rural land (68%) compared to the midsouth (Table 2). The Midwest's vastly different rural and urban land-use development character contributes to annual tornado impact variability by producing years where many HUs were affected by tornadoes as well as years where very few HUs were impacted. Annual tornado impact variability in the midsouth is expected to surpass the Midwest sometime between 2030 and 2090 due to the midsouth's rapid ex-urban land growth (Figs. 3c,g). The midsouth's impact standard deviation is predicted to increase anywhere from 2277% to 3514%, the largest change among all regions over the 1940–2100 period (Table 1). Overall, this transition occurs sooner in the A1 and A2 scenarios

TABLE 2. Total number of housing units and percentage of developable area in the at-risk regions for 1940 and 2100 (by the A2 SRES scenario). Land-use type was defined after Theobald (2005) as rural (>16.18 ha HU^{-1}); exurban (0.68 – 16.18 ha HU^{-1}); suburban (0.1 – 0.68 ha HU^{-1}); and urban (<0.1 ha HU^{-1}). The percentage change in total HUs and percentage of total developable area from 1940 to 2100 by regional study area and LU classification is also provided.

Region	Land-use class	Housing units			% of total developable area		
		1940	2100	% change 1940–2100	1940	2100	% change 1940–2100
Central plains	Rural	225 151	463 303	105.8	97.9	79.7	–18.6
	Exurban	209 650	2 110 166	906.5	1.9	16.1	764.5
	Suburban	445 246	6 725 928	1410.6	0.3	3.4	1215.9
	Urban	172 994	6 550 397	3686.5	0.01	0.8	3341.7
High plains	Rural	38 557	140 059	263.3	99.5	95.3	–4.3
	Exurban	51 746	577 692	1016.4	0.4	3.5	803.9
	Suburban	110 795	1 448 352	1207.2	0.1	0.7	801.6
Midsouth	Urban	37 055	3 969 748	10 613.2	0.01	0.5	9903.0
	Rural	189 375	564 958	198.3	98.0	65.0	–33.6
	Exurban	205 999	3 485 395	1591.9	1.9	30.1	1487.7
	Suburban	194 055	7 396 803	3711.7	0.1	3.6	2439.3
Midwest	Urban	42 538	9 675 024	22 644.5	0.01	1.3	22 917.4
	Rural	386 297	629 393	62.9	94.5	67.9	–28.1
	Exurban	537 898	2 791 839	419.0	4.6	25.8	456.6
	Suburban	1 235 604	10 796 096	773.8	0.8	4.9	526.9
	Urban	703 094	10 644 427	1413.9	0.1	1.4	1522.5

as these are based on more rapid economic progression, a highly mobile workforce, and strong domestic and international migration (EPA 2009).

Because of the effects of decreasing HU growth rates in the Midwest and slowly increasing growth rates in the central plains during the twenty-first century, the central plains and Midwest projected annual impact variability trends follow similar trajectories. The central plains' impact standard deviation is estimated to increase up to 7613% from 1940 to 2100; the Midwest's impact variability is expected to change by as much as 6280% (Table 1). The central plains annual tornado impact variability is constrained because of the paucity of the large population centers necessary for rapid HU growth, and the Midwest variability is restricted because vast amount of agricultural and protected land that tends to limit HU growth and sprawl (Brown et al. 2005). The high plains contain the least amount of annual HU impact variability compared to all other regions due to the paucity of large population centers, high proportion of rural land, and lower development growth rates (EPA 2009).

c. Tornado impact 95th percentile

The 95th percentile of annual impacts highlights the probability of high-end years where the number of HUs impacted by significant tornadoes would be considered either rare or relatively extreme by meteorologists and risk analysts (Figs. 3d,h, S1–S3). The potential for a high-end tornado impact year may be the result of a large number of tornadoes accompanying a severe

weather outbreak (e.g., 3–4 April 1974 and 27 April 2011 outbreaks) or a year where a single large tornado traversed a highly populated area resulting in thousands of HUs affected. From 1940 to 2000, the Midwest had the greatest absolute change in the 95th percentile, increasing by 9426 HUs, or 394% (Table 1; Figs. 3d,h). The midsouth is projected to overtake the Midwest during the twenty-first century for all projected ICLUS storylines except for B2. Annual HU impacts associated with the midsouth's 95th percentile may increase as much as 3468% from 1940 to 2100, while the Midwest may amplify up to 757% (Table 1). The more substantial growth in exurban land, higher domestic migration, and larger population growth rates found in the midsouth yield greater changes in 95th percentile tornado impacts compared to all other regions. Although less than the midsouth, the central plains' and high plains' 95th percentile annual HU impact values are expected to increase throughout the century, increasing by as much as 1480% and 2608%, respectively (Table 1; Figs. 3d,h). These comparisons indicate that although the Midwest contains a greater number of HUs today, high-end tornado impact probabilities for the other regions may increase at a much faster pace during the twenty-first century.

d. Observed versus uniform development types

To assess the relative influences of HU growth and spatial distribution on annual tornado impact probabilities, the TorMC was used to generate four 10 000-yr tornado simulations [two per decadal cost surface (1950 and 2100) over each region (Fig. 4)]. Simulations are

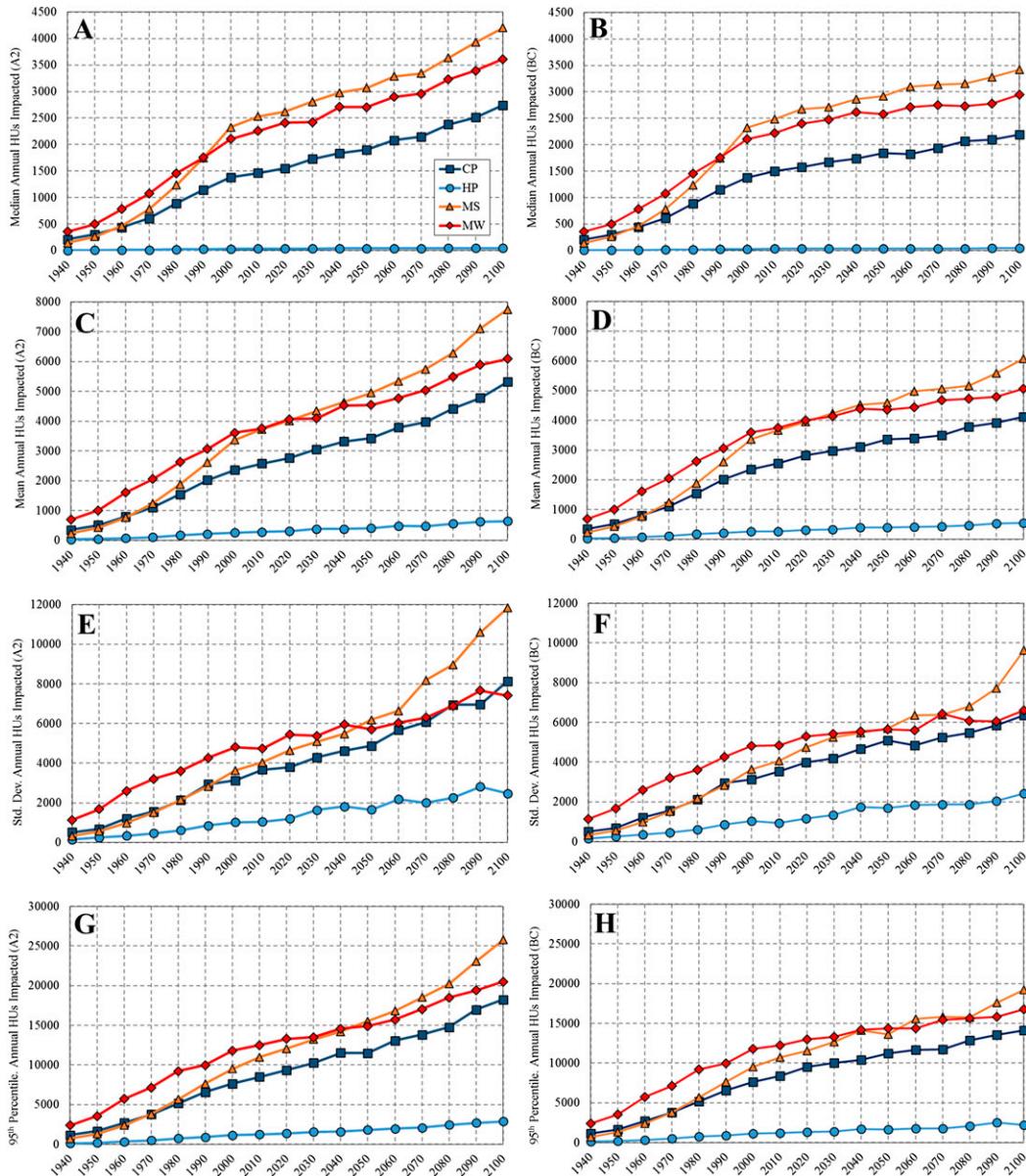


FIG. 3. Annual significant tornado impact descriptive statistics, including (a) median (A2), (b) median (BC), (c) mean (A2), (d) mean (BC), (e) standard deviation (A2), (f) standard deviation (BC), (g) 95th percentile (A2), and (h) 95th percentile (BC) for the central plains (squares), high plains (circles), midsouth (triangles), and Midwest (diamonds) from 1940 to 2100.

conducted over two types of hazard costs surfaces: observed and uniform. The observed cost surfaces are based on historical development and land-use patterns in each region. The uniform cost surfaces represent an extremely sprawled and theoretical HU density landscape, where the total number of HUs within the region for a given decade surface is distributed uniformly across the region’s spatial domain. Although the uniform cost surface is an unrealistic and theoretical land-use pattern, it does provide insight into how urban sprawl influences

tornado impacts and disaster probability. POE curves generated from the observed cost surface simulations capture both the effects of HU magnitude and sprawling development on tornado impact probability, while the uniform cost surface simulations highlight the effects of sprawl on tornado disaster potential. The differences between the 1950 and 2100 POE curves indicate the importance of HU magnitude growth during the 150-yr period, and the disparity in POE shapes portend the consequences of development and land-use differences.

TABLE 3. Absolute and percentage change in HUs for the at-risk regions.

Region	SRES scenario	Absolute change ($\times 1\,000\,000$)				Percentage change (%)			
		1940–2000	2000–50	2050–2100	1940–2100	1940–2000	2000–50	2050–2100	1940–2100
Central plains	A1	6.1	4.0	1.9	11.9	581.0	55.2	16.7	1133.4
	A2	6.1	3.3	5.4	14.8	581.0	45.5	51.9	1405.1
	B1	6.1	3.1	1.3	10.5	581.0	43.6	12.6	1000.5
	B2	6.1	2.4	2.1	10.6	581.0	33.4	22.0	1007.7
	BC	6.1	2.7	2.5	11.4	581.0	38.2	25.2	1078.3
High plains	A1	1.9	1.9	1.0	4.7	802.8	86.1	24.1	1984.7
	A2	1.9	1.6	2.4	5.9	802.8	72.6	65.3	2476.4
	B1	1.9	1.4	0.7	4.0	802.8	64.0	20.6	1685.0
	B2	1.9	1.1	1.2	4.2	802.8	53.1	36.1	1782.0
	BC	1.9	1.3	1.4	4.6	802.8	61.9	38.9	1930.3
Midsouth	A1	8.5	5.1	3.0	16.6	1351.7	55.2	20.9	2624.7
	A2	8.5	4.4	7.6	20.5	1351.7	47.4	56.1	3242.3
	B1	8.5	3.4	1.5	13.4	1351.7	37.3	11.8	2128.1
	B2	8.5	2.9	2.5	13.9	1351.7	31.3	20.8	2203.9
	BC	8.5	3.5	3.4	15.5	1351.7	38.2	26.9	2445.4
Midwest	A1	11.4	3.9	1.3	16.6	397.3	27.4	7.1	578.7
	A2	11.4	3.9	6.7	22.0	397.3	27.6	36.8	767.6
	B1	11.4	3.4	0.8	15.5	397.3	23.6	4.4	541.7
	B2	11.4	3.1	2.4	16.9	397.3	21.7	13.8	588.5
	BC	11.4	3.2	2.6	17.1	397.3	22.4	14.6	597.7

Comparing tornado impact statistics (Fig. 4) and POE curve shapes associated with each simulation reveals that the uniform cost surfaces contain greater mean annual tornado impacts compared to the observed cost surfaces. This suggests that although the total number of HUs in each region is equal in both the observed and uniform simulation scenarios, the uniform HU density pattern results in a greater number of HUs affected per year on average. Concurrently, high-impact years ($POE < 0.1$) in the uniform simulations are restricted due to the lack of clustered development (towns, cities, etc.). The total number of HUs affected by a single tornado on the uniform cost surface is related to tornado footprint areal coverage (i.e., the longer and wider simulated tornado, the greater the HU impact magnitude). The differences between observed and uniform high-impact years are revealed by comparing their standard deviations. The variability in annual tornado impacts is greater in observed simulations compared to the uniform simulations in all regions. In general, solely increasing HUs through time will lead to greater median and mean tornado–HU impacts, but incorporating clustered HU growth combined with sprawling development increases impact variability and high-impact event probability.

4. Discussion and conclusions

While the findings presented reveal the potential for more and greater tornado disasters in the future, disaster risk probability is not uniform across space and time. In

general, comparative results across at-risk regions reveal that future tornado disaster potential will be greatest in the midsouth because of this region’s elevated tornado risk intersecting heightened exposure rates because of existing and projected built-environment development in and around metropolitan areas. The south contains a large number of physical and social vulnerabilities—from a high rate of nighttime tornadoes and fast storm speeds to substantial mobile home density and elevated poverty rates (Ashley 2007; Simmons and Sutter 2007; Ashley et al. 2008). Any increase in residential built environment and affiliated population will amplify these vulnerabilities, portending greater disaster frequency and magnitude in the future. While this potential is greatest in the midsouth, the other at-risk regions investigated reveal similar trends in disaster likelihood as varying—but generally increasing—rates of exposure interact with some of the highest tornado risks anywhere in the world (Brooks et al. 2003b; Tippett et al. 2015).

Understanding how disasters are being altered is complex because of changes in vulnerability and risk (Meehl et al. 2000; IPCC 2001, 2012). The relationship between these disaster constituents is best illustrated by examining their respective statistical distributions rather than just central tendency and variability (e.g., IPCC 2001, their Fig. 2.32). A simple conceptual model highlights how tornado impact POE may change under future development regimes (Fig. 5). Within each curve, there are individual shifts in tornado central tendency and variability, all related to residential

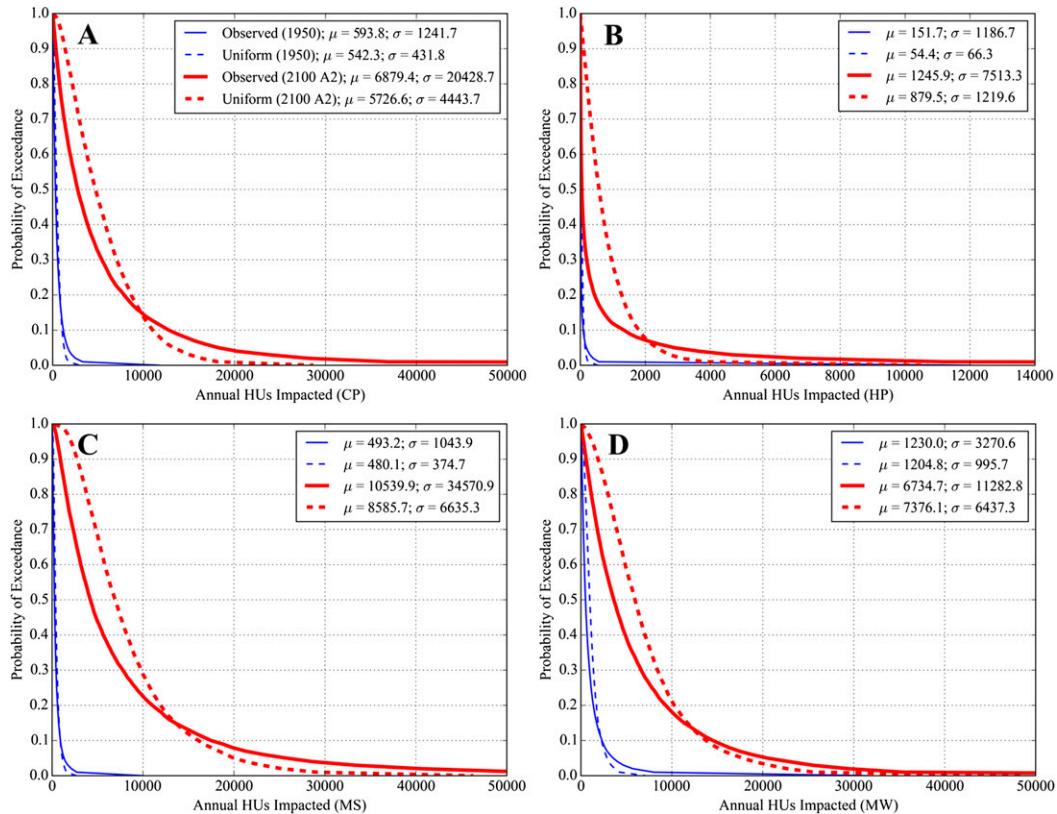


FIG. 4. As in Fig. 2, but for 1950 (thin lines) and 2100 (thicker lines; A2 SRES scenario). The dashed lines illustrate the POE curves from uniform HU distributions and solid lines highlight observed HU density patterns derived from the SERGoM-ICLUS cost surfaces for 1950 and 2100 (A2). The mean μ and standard deviation σ for each POE curve are also presented.

built-environment growth and development patterns (Fig. 5a). Figure 5b isolates the effects of differing development types on the central tendency and variability measures of tornado exposure. Scenario 1 (Fig. 5b; t_{1a}) is indicative of a landscape that contains a large amount of urban density loss or urban flight (e.g., Cullen and Levitt 1999) and increasingly uniform HU density (i.e., faster HU growth on the fringes of metropolitan areas compared to the inner city), leading to greater central tendency of tornado impact and less variability. Scenario 2 (Fig. 5b; t_{1b}) illustrates tornado impact increases through the clustering of population and HUs (i.e., migration back to urban cores and/or smart growth development; Atkinson and Bridge 2005) while decreasing sprawl. This scenario leads to no change in future tornado impact central tendency but increased impact variability. Last, scenario 3 (Fig. 5b; t_{1c}) represents expected future development growth with escalations in both central tendency and variability. The spatial character of population and built-environment growth is also exceedingly important in creating tornado disaster potential. Increasing the number of people and/or HUs will lead to

more amplified tornado impacts and greater disaster potential. However, landscapes that contain clustering of population and housing, such as that found in traditional city morphologies, yield more variable tornado impact magnitudes and greater potential for high-end (>1000 HU affected) tornado events. Conversely, landscapes that contain a larger amount of sprawl and less built-environment clustering typically have greater mean and median tornado impacts but are less likely to experience high-end tornado events. The implication of development morphology and its speed as a fingerprint of disaster potential suggests that city managers, urban planners, catastrophe modelers, and policy makers should be examining the spatial character of land use alongside potential changes in hazard risk due to climate change (e.g., IPCC 2014; Herring et al. 2015).

Many current tornado disaster mitigation strategies place a majority of effort on short-term preparedness and response (e.g., Millie et al. 2000; Sorensen 2000; Doswell and Brooks 2002; der Heide 2006; Collins and Kapucu 2008). However, additional efforts should be placed on medium- and long-term horizon (i.e., years

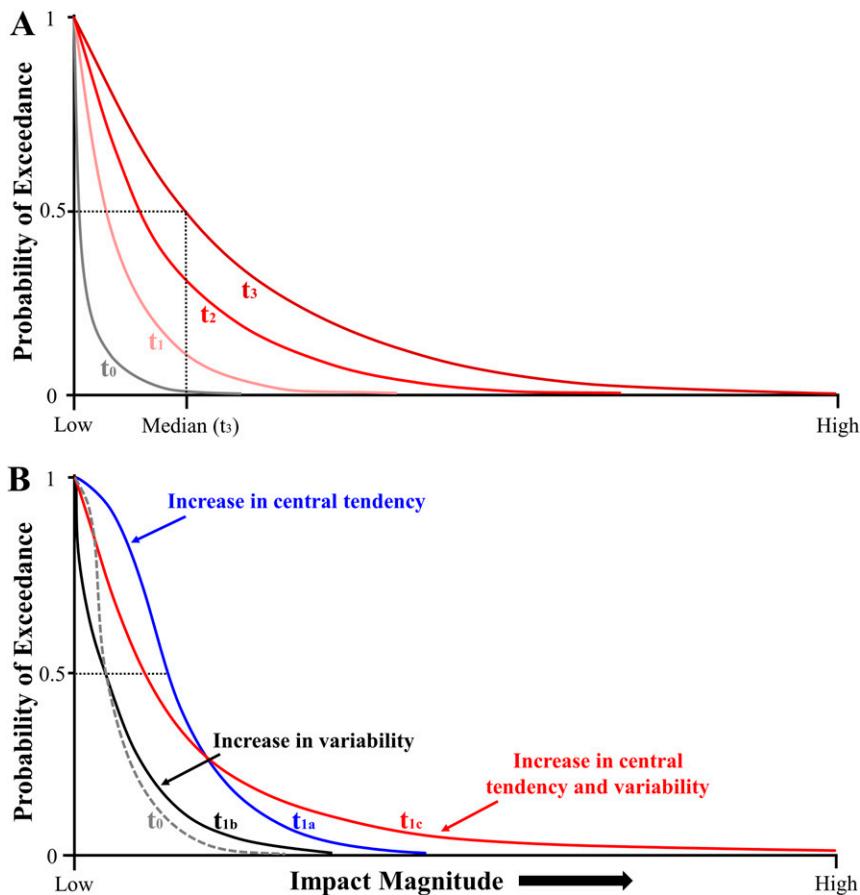


FIG. 5. Theoretical POE curves for a tornado impacting a number of HU. (a) How the impact POE curves are expected change provided future population and built-environment growth. (b) The influence of HU magnitude growth or HU sprawl on the shape of the POE. Curve t_0 represents the current day tornado impact POE, t_{1a} highlights an increase in tornado impact central tendency but no amplification in variability, t_{1b} indicates inflating tornado impact variability but no increase in central tendency, and t_{1c} exemplifies amplifications in both tornado impact central tendency and variability.

and decades prior to an event) activities such as land planning and infrastructure mitigation strategies. For instance, communities and regions prone to tornado hazards should more readily consider tornado disaster probabilities and exposure within their disaster mitigation strategies, practices, and techniques. If possible, the adoption of land-use planning aimed at mitigating tornado disaster effects, and improving individual, community, and institutional resilience, could not only be beneficial economically, but also lead to decreased consequences when a tornado, or other environmental hazard, occurs. The continual investment in safe rooms, public shelters, and improvements in construction practices that enhance tornado survivability should also remain a priority (Merrell et al. 2002; Paton and Johnston 2006; Simmons and Sutter 2007; Prevatt et al. 2012; Simmons et al. 2015).

The IPCC SRES storylines and their inclusion in this analysis permitted an assessment of various socioeconomic pathways on future tornado disaster consequences. For regions and communities that are projected to undergo rapid built-environment growth and sprawl, long-term development plans and strategies should be considered in the face of both changing hazard risk (Kunkel et al. 2013) and exposure to mitigate future disaster consequences (Tippett et al. 2015). While changing existing, or implementing new, land-use practices related to reducing hazard exposure and disaster potential is a challenging task for many communities, an emphasis should be placed on how possible changes in built-environment growth may interact with the anticipated effects of climate change on hazard risk. Including discussions of land-use policy and its disaster influence alongside policy related to climate change and possible

shifts in hazard risk will permit decision-makers and elected officials to make more informed decisions about how to better prepare for and mitigate future disasters.

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REFERENCES

- Abbey, R., Jr., and T. Fujita, 1975: Use of tornado path lengths and gradations of damage to assess tornado intensity probabilities. Preprints, *Ninth Conf. on Severe Local Storms*, Norman, OK, Amer. Meteor. Soc., 286–293.
- , and —, 1979: The DAPPLE method for computing tornado hazard probabilities: Refinements and theoretical considerations. Preprints, *11th Conf. on Severe Local Storms*, Kansas City, MO, Amer. Meteor. Soc., 241–248.
- Agee, E., and S. Childs, 2014: Adjustments in tornado counts, F-scale intensity, and path width for assessing significant tornado destruction. *J. Appl. Meteor. Climatol.*, **53**, 1494–1505, doi:10.1175/JAMC-D-13-0235.1.
- Ashley, W., 2007: Spatial and temporal analysis of tornado fatalities in the United States: 1880–2005. *Wea. Forecasting*, **22**, 1214–1228, doi:10.1175/2007WAF2007004.1.
- , and S. Strader, 2016: Recipe for disaster: How the dynamic ingredients of risk and exposure are changing the tornado disaster landscape. *Bull. Amer. Meteor. Soc.*, 767–786, doi:10.1175/BAMS-D-15-00150.1.
- , A. Krmenc, and R. Schwantes, 2008: Vulnerability due to nocturnal tornadoes. *Wea. Forecasting*, **23**, 795–807, doi:10.1175/2008WAF2222132.1.
- , S. Strader, T. Rosencrants, and A. Krmenc, 2014: Spatio-temporal changes in tornado hazard exposure: The case of the expanding bull's eye effect in Chicago, IL. *Wea. Climate Soc.*, **6**, 175–193, doi:10.1175/WCAS-D-13-00047.1.
- Atkinson, R., and G. Bridge, 2005: *Gentrification in a Global Context*. Routledge, 320 pp.
- Bierwagen, B., D. Theobald, C. Pyke, A. Choate, P. Groth, J. Thomas, and P. Morefield, 2010: National housing and impervious surface scenarios for integrated climate impact assessments. *Proc. Natl. Acad. Sci. USA*, **107**, 20 887–20 892, doi:10.1073/pnas.1002096107.
- Bouwer, L., 2011: Have disaster losses increased due to anthropogenic climate change? *Bull. Amer. Meteor. Soc.*, **92**, 39–46, doi:10.1175/2010BAMS3092.1.
- Brooks, H., 2004: On the relationship of tornado path length and width to intensity. *Wea. Forecasting*, **19**, 310–319, doi:10.1175/1520-0434(2004)019<0310:OTROTP>2.0.CO;2.
- , C. Doswell III, and M. Kay, 2003a: Climatological estimates of local daily tornado probability. *Wea. Forecasting*, **18**, 626–640, doi:10.1175/1520-0434(2003)018<0626:CEOLDT>2.0.CO;2.
- , J. Lee, and J. Craven, 2003b: The spatial distribution of severe thunderstorm and tornado environments from global reanalysis data. *Atmos. Res.*, **67–68**, 73–94, doi:10.1016/S0169-8095(03)00045-0.
- , G. Carbin, and P. Marsh, 2014: Increased variability of tornado occurrence in the United States. *Science*, **346**, 349–352, doi:10.1126/science.1257460.
- Brown, D., K. Johnson, T. Loveland, and D. Theobald, 2005: Rural land-use trends in the conterminous United States, 1950–2000. *Ecol. Appl.*, **15**, 1851–1863, doi:10.1890/03-5220.
- Burkett, V., and M. Davidson, 2012: Coastal impacts, adaptation and vulnerability: A technical input to the 2012 National Climate Assessment. Cooperative Rep. to the 2013 National Climate Assessment, 150 pp.
- Cai, Q., G. Rushton, B. Bhaduri, E. Bright, and P. Coleman, 2006: Estimating small-area populations by age and sex using spatial interpolation and statistical inference methods. *Trans. GIS*, **10**, 577–598, doi:10.1111/j.1467-9671.2006.01013.x.
- Changnon, S., and J. Burroughs, 2003: The tristate hailstorm: The most costly on record. *Mon. Wea. Rev.*, **131**, 1734–1739, doi:10.1175/2549.1.
- , R. Pielke Jr., D. Changnon, R. Sylves, and R. Pulwarty, 2000: Human factors explain the increased losses from weather and climate extremes. *Bull. Amer. Meteor. Soc.*, **81**, 437–442, doi:10.1175/1520-0477(2000)081<0437:HFETIL>2.3.CO;2.
- Coleman, T., and P. Dixon, 2014: An objective analysis of tornado risk in the United States. *Wea. Forecasting*, **29**, 366–376, doi:10.1175/WAF-D-13-00057.1.
- Collins, M., and N. Kapucu, 2008: Early warning systems and disaster preparedness and response in local government. *Disaster Prev. Manage.*, **17**, 587–600, doi:10.1108/09653560810918621.
- Cullen, J. B., and S. D. Levitt, 1999: Crime, urban flight, and the consequences for cities. *Rev. Econ. Stat.*, **81**, 159–169, doi:10.1162/003465399558030.
- Cutter, S., C. Emrich, J. Webb, and D. Morath, 2009: Social vulnerability to climate variability hazards: A review of the literature. Final Rep. to Oxfam America, 44 pp.
- Daneshvaran, S., and R. Morden, 2007: Tornado risk analysis in the United States. *J. Risk Finance*, **8**, 97–111, doi:10.1108/15265940710732314.
- der Heide, E. A., 2006: The importance of evidence-based disaster planning. *Ann. Emerg. Med.*, **47**, 34–49, doi:10.1016/j.annemergmed.2005.05.009.
- Diffenbaugh, N., M. Scherer, and R. Trapp, 2013: Robust increases in severe thunderstorm environments in response to greenhouse forcing. *Proc. Natl. Acad. Sci. USA*, **110**, 16 361–16 366, doi:10.1073/pnas.1307758110.
- Dixon, P., and A. Mercer, 2012: Reply to “Comments on ‘Tornado risk analysis: Is Dixie Alley an extension of Tornado Alley?’” *Bull. Amer. Meteor. Soc.*, **93**, 408–410, doi:10.1175/BAMS-D-11-00219.1.
- , —, J. Choi, and J. Allen, 2011: Tornado risk analysis: Is Dixie Alley an extension of Tornado Alley? *Bull. Amer. Meteor. Soc.*, **92**, 433–441, doi:10.1175/2010BAMS3102.1.
- Doswell, C., III, 2007: Small sample size and data quality issues illustrated using tornado occurrence data. *Electron. J. Severe Storms Meteor.*, **2**, 1–16.
- , and H. Brooks, 2002: Lessons learned from the damage produced by the tornadoes of 3 May 1999. *Wea. Forecasting*, **17**, 611–618, doi:10.1175/1520-0434(2002)017<0611:LLFTDP>2.0.CO;2.
- , —, and M. Kay, 2005: Climatological estimates of daily local nontornadic severe thunderstorm probability for the United States. *Wea. Forecasting*, **20**, 577–595, doi:10.1175/WAF866.1.
- Edwards, R., J. LaDue, J. Ferree, K. Scharfenberg, C. Maier, and W. Coulbourne, 2013: Tornado intensity estimation: Past, present, and future. *Bull. Amer. Meteor. Soc.*, **94**, 641–653, doi:10.1175/BAMS-D-11-00006.1.

- Elsner, J., L. Michaels, K. Scheitlin, and I. Elsner, 2013: The decreasing population bias in tornado reports across the central plains. *Wea. Climate Soc.*, **5**, 221–232, doi:[10.1175/WCAS-D-12-00040.1](https://doi.org/10.1175/WCAS-D-12-00040.1).
- , T. Jagger, H. Widen, and D. Chavas, 2014: Daily tornado frequency distributions in the United States. *Environ. Res. Lett.*, **9**, 024018, doi:[10.1088/1748-9326/9/2/024018](https://doi.org/10.1088/1748-9326/9/2/024018).
- EPA, 2009: Land-use scenarios: National-scale housing-density scenarios consistent with climate change storylines. EPA Final Rep. EPA/600/R-08/076F, 137 pp.
- Farney, T. J., and P. G. Dixon, 2015: Variability of tornado climatology across the continental United States. *Int. J. Climatol.*, **35**, 2993–3006, doi:[10.1002/joc.4188](https://doi.org/10.1002/joc.4188).
- Finley, J., 1887: *Tornadoes: What They Are and How to Observe Them*. Insurance Monitor Press, 196 pp.
- Fujita, T. T., 1981: Tornadoes and downbursts in the context of generalized planetary scales. *J. Atmos. Sci.*, **38**, 1511–1534, doi: [10.1175/1520-0469\(1981\)038<1511:TADITC>2.0.CO;2](https://doi.org/10.1175/1520-0469(1981)038<1511:TADITC>2.0.CO;2).
- Gagan, J., A. Gerard, and J. Gordon, 2010: A historical and statistical comparison of “Tornado Alley” to “Dixie Alley.” *Natl. Wea. Dig.*, **34**, 145–155.
- Gensini, V., and T. Mote, 2015: Downscaled estimates of late 21st century severe weather from CCSM3. *Climatic Change*, **129**, 307–321, doi:[10.1007/s10584-014-1320-z](https://doi.org/10.1007/s10584-014-1320-z).
- Grazulis, T., 1993: *Significant Tornadoes, 1680-1991*. Environmental Films, 1340 pp.
- Hall, S., and W. Ashley, 2008: The effects of urban sprawl on the vulnerability to a significant tornado impact in northeastern Illinois. *Nat. Hazards Rev.*, **9**, 209–219, doi:[10.1061/\(ASCE\)1527-6988\(2008\)9:4\(209\)](https://doi.org/10.1061/(ASCE)1527-6988(2008)9:4(209)).
- Herring, S., M. Hoerling, J. Kossin, T. Peterson, and P. Scott, 2015: Explaining extreme events of 2014 from a climate perspective. *Bull. Amer. Meteor. Soc.*, **96** (12), S1–S172.
- Höppe, P., and R. Pielke Jr., Eds., 2006: Workshop on climate change and disaster losses: Understanding and attributing trends and projections. Final workshop report, 270 pp.
- IPCC, 2001: *Climate Change 2001: The Scientific Basis*. Cambridge University Press, 881 pp.
- , 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. Cambridge University Press, 582 pp.
- , 2014: *Climate Change 2014: Mitigation of Climate Change*. Cambridge University Press, 1465 pp. [Available online at http://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_full.pdf.]
- Kunkel, K., and Coauthors, 2013: Monitoring and understanding trends in extreme storms: State of knowledge. *Bull. Amer. Meteor. Soc.*, **94**, 499–514, doi:[10.1175/BAMS-D-11-00262.1](https://doi.org/10.1175/BAMS-D-11-00262.1).
- Manson, G. A., and R. E. Groop, 2000: U.S. intercounty migration in the 1990s: People and income move down the urban hierarchy. *Prof. Geogr.*, **52**, 493–504, doi:[10.1111/0033-0124.00241](https://doi.org/10.1111/0033-0124.00241).
- Marsh, P., and H. Brooks, 2012: Comments on “Tornado risk analysis: Is Dixie Alley an extension of Tornado Alley?” *Bull. Amer. Meteor. Soc.*, **93**, 405–407, doi:[10.1175/BAMS-D-11-00200.1](https://doi.org/10.1175/BAMS-D-11-00200.1).
- Meehl, G., F. Zwiers, J. Evans, T. Knutson, L. Mearns, and P. Whetton, 2000: Trends in extreme weather and climate events: Issues related to modeling extremes in projections of future climate change. *Bull. Amer. Meteor. Soc.*, **81**, 427–436, doi:[10.1175/1520-0477\(2000\)081<0427:TIEWAC>2.3.CO;2](https://doi.org/10.1175/1520-0477(2000)081<0427:TIEWAC>2.3.CO;2).
- Merrell, D., K. Simmons, and D. Sutter, 2002: Taking shelter: Estimating the safety benefits of tornado safe rooms. *Wea. Forecasting*, **17**, 619–625, doi:[10.1175/1520-0434\(2002\)017<0619:TSETSB>2.0.CO;2](https://doi.org/10.1175/1520-0434(2002)017<0619:TSETSB>2.0.CO;2).
- Meyer, C., H. Brooks, and M. Kay, 2002: A hazard model for tornado occurrence in the United States. Preprints, *16th Conf. on Probability and Statistics*, Orlando, FL, Amer. Meteor. Soc., J3.6. [Available online at https://ams.confex.com/ams/annual2002/techprogram/paper_27595.htm.]
- Millie, M., C. Senkowski, L. Stuart, and F. Davis, 2000: Tornado disaster in rural Georgia: Triage response, injury patterns, lessons learned. *Amer. Surg.*, **66**, 223–228.
- Mohleji, S., and R. Pielke Jr., 2014: Reconciliation of trends in global and regional economic losses from weather events: 1980–2008. *Nat. Hazards Rev.*, **15**, doi:[10.1061/\(ASCE\)NH.1527-6996.0000141](https://doi.org/10.1061/(ASCE)NH.1527-6996.0000141).
- Mooney, C., 1997: *Monte Carlo Simulation*. Sage Publications, 112 pp.
- Morss, R., O. Wilhelmi, G. Meehl, and L. Dilling, 2011: Improving societal outcomes of extreme weather in a changing climate: An integrated perspective. *Annu. Rev. Environ. Resour.*, **36**, 1–25, doi:[10.1146/annurev-enviro-060809-100145](https://doi.org/10.1146/annurev-enviro-060809-100145).
- National Academies of Science Engineering and Medicine, 2016: *Attribution of Extreme Weather Events in the Context of Climate Change*. National Academies Press, 186 pp.
- Paton, D., and D. Johnston, 2006: *Disaster Resilience: An Integrated Approach*. Thomas Books, 320 pp.
- Paul, B., 2011: *Environmental Hazards and Disasters: Contexts, Perspectives and Management*. John Wiley & Sons, 334 pp.
- Paulikas, M. J., and W. S. Ashley, 2011: Thunderstorm hazard vulnerability for the Atlanta, Georgia metropolitan region. *Nat. Hazards*, **58**, 1077–1092, doi:[10.1007/s11069-010-9712-5](https://doi.org/10.1007/s11069-010-9712-5).
- Peterson, T., and Coauthors, 2013: Monitoring and understanding changes in heat waves, cold waves, floods, and droughts in the United States: State of knowledge. *Bull. Amer. Meteor. Soc.*, **94**, 821–834, doi:[10.1175/BAMS-D-12-00066.1](https://doi.org/10.1175/BAMS-D-12-00066.1).
- Pielke, R., Jr., 2005: Attribution of disaster losses. *Science*, **310**, 1615–1616, doi:[10.1126/science.310.5754.1615c](https://doi.org/10.1126/science.310.5754.1615c).
- Preston, B., 2013: Local path dependence of U.S. socioeconomic exposure to climate extremes and the vulnerability commitment. *Global Environ. Change*, **23**, 719–732, doi:[10.1016/j.gloenvcha.2013.02.009](https://doi.org/10.1016/j.gloenvcha.2013.02.009).
- Prevatt, D., and Coauthors, 2012: Making the case for improved structural design: Tornado outbreaks of 2011. *Leadership Manage. Eng.*, **12**, 254–270, doi:[10.1061/\(ASCE\)LM.1943-5630.0000192](https://doi.org/10.1061/(ASCE)LM.1943-5630.0000192).
- Rae, S., and J. Stefkovich, 2000: The tornado damage risk assessment predicting the impact of a big outbreak in Dallas–Fort Worth, Texas. Preprints, *20th Conf. on Severe Local Storms*, Orlando, FL, Amer. Meteor. Soc., 295–296. [Available online at https://ams.confex.com/ams/Sept2000/techprogram/paper_16405.htm.]
- Robinson, E., R. Trapp, and M. Baldwin, 2013: The geospatial and temporal distributions of severe thunderstorms from high-resolution dynamical downscaling. *J. Appl. Meteor. Climatol.*, **52**, 2147–2161, doi:[10.1175/JAMC-D-12-0131.1](https://doi.org/10.1175/JAMC-D-12-0131.1).
- Rosencrants, T., and W. Ashley, 2015: Spatiotemporal analysis of tornado exposure in five US metropolitan areas. *Nat. Hazards*, **78**, 121–140, doi:[10.1007/s11069-015-1704-z](https://doi.org/10.1007/s11069-015-1704-z).
- Schaefer, J., D. Kelly, and R. Abbey, 1986: A minimum assumption tornado-hazard probability model. *J. Appl. Meteor.*, **25**, 1934–1945, doi:[10.1175/1520-0450\(1986\)025<1934:AMATHP>2.0.CO;2](https://doi.org/10.1175/1520-0450(1986)025<1934:AMATHP>2.0.CO;2).
- Simmons, K., and D. Sutter, 2007: Tornado shelters and the housing market. *Constr. Manage. Econ.*, **25**, 1119–1126, doi:[10.1080/01446190701618299](https://doi.org/10.1080/01446190701618299).
- , and —, 2011: *Economic and Societal Impacts of Tornadoes*. Amer. Meteor. Soc., 282 pp.
- , —, and R. Pielke, 2013: Normalized tornado damage in the United States: 1950–2011. *Environ. Hazards*, **12**, 132–147, doi:[10.1080/17477891.2012.738642](https://doi.org/10.1080/17477891.2012.738642).

- , —, P. Kovacs, and G. Kopp, 2015: Tornado damage mitigation: Benefit–cost analysis of enhanced building codes in Oklahoma. *Wea. Climate Soc.*, **7**, 169–178, doi:[10.1175/WCAS-D-14-00032.1](https://doi.org/10.1175/WCAS-D-14-00032.1).
- Smith, B., R. Thompson, J. Grams, C. Broyles, and H. Brooks, 2012: Convective modes for significant severe thunderstorms in the contiguous United States. Part I: Storm classification and climatology. *Wea. Forecasting*, **27**, 1114–1135, doi:[10.1175/WAF-D-11-00115.1](https://doi.org/10.1175/WAF-D-11-00115.1).
- Sorensen, J., 2000: Hazard warning systems: Review of 20 years of progress. *Nat. Hazards Rev.*, **1**, 119–125, doi:[10.1061/\(ASCE\)1527-6988\(2000\)1:2\(119\)](https://doi.org/10.1061/(ASCE)1527-6988(2000)1:2(119)).
- Strader, S., and W. Ashley, 2015: The expanding bull’s eye effect. *Weatherwise*, **68**, 23–29, doi:[10.1080/00431672.2015.1067108](https://doi.org/10.1080/00431672.2015.1067108).
- , —, A. Irizarry, and S. Hall, 2015: A climatology of tornado intensity assessments. *Meteor. Appl.*, **22**, 513–524, doi:[10.1002/met.1482](https://doi.org/10.1002/met.1482).
- , T. Pingel, and W. Ashley, 2016: A Monte Carlo model for estimating tornado impacts. *Meteor. Appl.*, **23**, 269–281, doi:[10.1002/met.1552](https://doi.org/10.1002/met.1552).
- Theobald, D., 2005: Landscape patterns of exurban growth in the USA from 1980 to 2020. *Ecol. Soc.*, **10**, 32. [Available online at <http://www.ecologyandsociety.org/vol10/iss1/art32>.]
- Thom, H. C. S., 1963: Tornado probabilities. *Mon. Wea. Rev.*, **91**, 730–736, doi:[10.1175/1520-0493\(1963\)091<0730:TP>2.3.CO;2](https://doi.org/10.1175/1520-0493(1963)091<0730:TP>2.3.CO;2).
- Tippett, M., J. Allen, V. Gensini, and H. Brooks, 2015: Climate and hazardous convective weather. *Curr. Climate Change Rep.*, **1**, 60–73, doi:[10.1007/s40641-015-0006-6](https://doi.org/10.1007/s40641-015-0006-6).
- Trapp, R., and K. Hoogewind, 2016: The realization of extreme tornadic events under future anthropogenic climate change. *J. Climate*, **29**, 5251–5265, doi:[10.1175/JCLI-D-15-0623.1](https://doi.org/10.1175/JCLI-D-15-0623.1).
- , N. Diffenbaugh, H. Brooks, M. Baldwin, E. Robinson, and J. Pal, 2007: Changes in severe thunderstorm environment frequency during the 21st century caused by anthropogenically enhanced global radiative forcing. *Proc. Natl. Acad. Sci. USA*, **104**, 19 719–19 723, doi:[10.1073/pnas.0705494104](https://doi.org/10.1073/pnas.0705494104).
- , E. Robinson, M. Baldwin, N. Diffenbaugh, and B. Schwedler, 2011: Regional climate of hazardous convective weather through high-resolution dynamical downscaling. *Climate Dyn.*, **37**, 677–688, doi:[10.1007/s00382-010-0826-y](https://doi.org/10.1007/s00382-010-0826-y).
- Verbout, S., H. Brooks, L. Leslie, and D. Schultz, 2006: Evolution of the U.S. tornado database: 1954–2003. *Wea. Forecasting*, **21**, 86–93, doi:[10.1175/WAF910.1](https://doi.org/10.1175/WAF910.1).
- Wilson, S., and T. Fischetti, 2010: Coastline population trends in the United States: 1960 to 2008. U.S. Census Bureau P25-1139, 27 pp. [Available online at <https://www.census.gov/prod/2010pubs/p25-1139.pdf>.]
- Wolford, L. V., 1960: Tornado occurrence in the United States. U.S. Weather Bureau Tech. Paper 20, 71 pp. [Available from NOAA Central Library, Second Floor, 1315 East–West Hwy., Silver Spring, MD 20910.]
- Wurman, J., C. Alexander, P. Robinson, and Y. Richardson, 2007: Low-level winds in tornadoes and potential catastrophic tornado impacts in urban areas. *Bull. Amer. Meteor. Soc.*, **88**, 31–46, doi:[10.1175/BAMS-88-1-31](https://doi.org/10.1175/BAMS-88-1-31).