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ORIGINAL PAPER

# Spatiotemporal analysis of tornado exposure in five US metropolitan areas

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**Abstract** Weather-related disasters and affiliated losses in the USA have amplified over time. However, prior research using normalization schemes on damage tallies suggests that weather hazard losses are not necessarily rising when inflation, changes in wealth, and growth in population are accounted. This study evaluates the latter factor, assessing if population changes and a sprawling development mode have led to increasing potential for tornado disasters in the USA. Specifically, this research shows where and how quickly tornado exposure is growing by appraising spatiotemporal trends in gridded population and housing unit data for five metropolitan statistical areas (MSAs). The macroscale risk to tornadoes is represented by tornado day climatology and is related to the exposure of the five MSAs, which include Atlanta, GA; Chicago, IL; Dallas/Fort Worth, TX; Oklahoma City, OK; and St. Louis, MO. Supplementing the macroscale investigation, an observationally derived, hypothetical violent tornado track is transposed on various development types in each MSA to determine the microscale changes in human and built-environment exposure. Results demonstrate increased exposure in all MSAs at both the macro- and microscale. Of the five MSAs studied, Dallas, TX, had the greatest potential for a tornado disaster due to the higher risk for tornado occurrence comingling with the amount of MSA exposure. These results reveal further that amplifying exposure is a major impetus behind intensifying severe weather impacts and losses.

**Keywords** Hazards · Exposure · Tornado · Population dynamics

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## 1 Introduction

In 2011, the USA had 14 weather events—from drought, wildfire, tornado outbreaks, flooding to blizzards—that caused over $1 billion in damage (Smith and Katz 2013). Atmospheric and hazard scientists are now faced with a series of essential questions that have important implications for policy, mitigation, emergency management, insurance, and commerce. Are these high-end events the new normal? Are billion dollar weather events going to continue to increase, and if so, what are the root causes of the escalating disaster losses? Broadly, impacts from severe weather hazards in the USA are increasing despite large spatial and interannual variability in the losses associated with these hazards (Intergovernmental Panel on Climate Change 2012). Research examining the changes in the disaster landscape suggests that the amplification of disasters is driven largely by increases in population, wealth, and inflation (Kunkel et al. 1999; Changnon et al. 2000; Brooks and Doswell 2001; Pielke et al. 2008; Changnon 2010; Bouwer 2011; Simmons et al. 2013). Sprawl development, which has been a dominant growth mode in the USA the past 70 years, has led to the dramatic expansion of most metropolitan regions, placing more people and property in harm's way of geophysical hazards (Changnon and Burroughs 2003; Hall and Ashley 2008; Bouwer 2011; Morss et al. 2011; Paulikas and Ashley 2011; Ashley et al. 2014). Other studies have investigated possible climate change effects of microscale and mesoscale meteorological hazards (Trapp et al. 2007; Peterson et al. 2008; Kunkel et al. 2012; Brooks 2013; Diffenbaugh et al. 2013). However, there is no consensus on whether severe storm micro-hazards such as tornadoes will increase or decrease in frequency or magnitude, beyond that found with natural variability, in the near future (Brooks 2013). This study examines specifically the role development and its character has in affecting the human and residential built-environment exposure of relatively high-risk metropolitan areas to the tornado hazard and, ultimately, tornado disaster potentiality.

The research presented examines the spatiotemporal trends of tornado exposure across five metropolitan statistical areas (MSAs) in the USA decennially for 1960–2010 using gridded US Census Bureau block- and/or tract-level population and housing unit data. In addition, exposure metrics are calculated for 2020–2040 employing population and household count projections at the county level. Mean annual tornado day climatologies are superimposed atop the gridded population, housing unit, and household data (measures of exposure) to visually reference the overall risk for each MSA. Descriptive and geographical analyses of the gridded population and housing data are used to appraise the exposure changes. The research then focuses on the microscale by engaging hypothetical tornado paths to simulate tornado disaster scenarios across the MSAs. A hypothetical tornado is derived from mean historical width statistics of contemporary violent tornadoes in addition to damage indicators from the May 22, 2011, Joplin, MO EF5 tornado. The overarching goal of the research is to test the hypothesis that changes in exposure are a driving force in increased human impacts due to severe storm hazards. Specifically, we evaluate how US development characteristics and trends have led to increasing and expanding exposure to the tornado hazard. This so-called expanding bull's eye effect concept suggests that "targets"—i.e., humans, their possessions, and affiliated infrastructure—of hazards are expanding as metropolitan regions grow and spread (Ashley et al. 2014).

## 2 Data and methods

Changes in exposure to tornadoes are examined within five MSAs: Atlanta, GA; Chicago, IL/IN/WI; Dallas/Fort Worth, TX; St. Louis, MO/IL; and Oklahoma City, OK (Fig. 1). These particular MSAs were chosen because they typify US urban development character

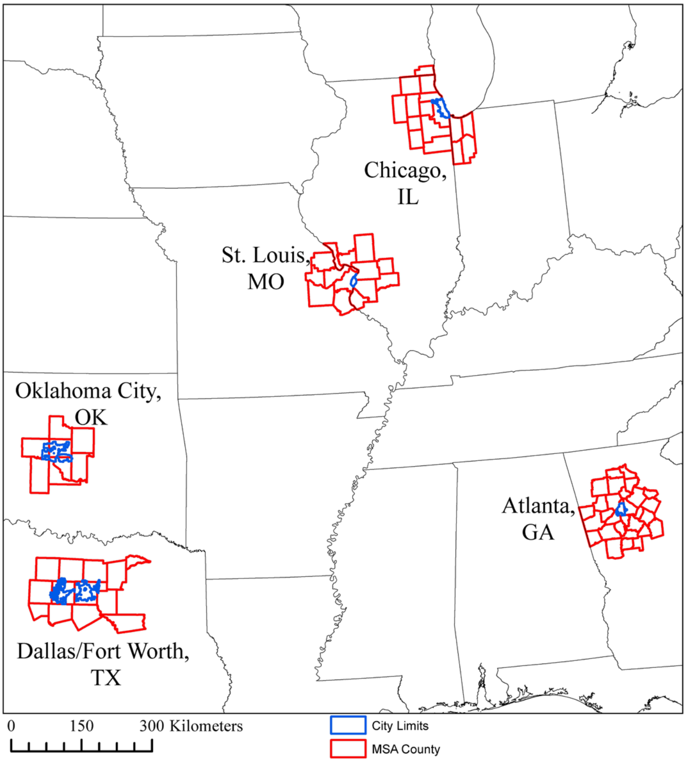

**Fig. 1** The counties of each MSA within the study area (*red*) and city limits (*blue*)

over the past half century and all contain relatively elevated tornado risk (Brooks et al. 2003). All five MSAs were among the top 50 largest growing urban complexes, in total population, from 1990 to 2010 (MSA—Rank: Atlanta—2; Chicago—10; Dallas/Fort Worth—1; Oklahoma City—43; St. Louis—48; United States Census Bureau 2011). In addition, the five MSAs are located in states having the most tornado catastrophes, which are events totaling over $1 million at the time of event according to the property claims services (Changnon 2009).

The analysis comprises three separate methods. First, census data are used in a gridded framework to assess macroscale spatiotemporal changes in exposure of the various MSAs. Second, tornado point data are used to generate spatial tornado day climatologies to examine tornado risk. Lastly, a hypothetical tornado path is employed to create potential tornado disaster scenarios within the five MSAs to represent microscale tornado risk.

## 2.1 Exposure changes

The investigation uses exposure (one attribute of a place's vulnerability; Morss et al. 2011) as a proxy to determine the effect vulnerability has on tornado disaster potential. Representation of exposure can be performed by mapping population or housing units over time using different areal units, such as states, counties, or census areal units (tracts or blocks). Census tracts are as homogenous as possible in terms of population characteristics, economic status, and living conditions and are delineated along visible features (e.g., rivers, roads). All census variables are available at the tract level, but the size of tracts is too large for neighborhood or microscale analysis (Schlossberg 2003). Blocks, which are the smallest census enumeration level, are located within tracts and also have boundaries that follow visible features. In general, the smaller size of blocks lends itself to be used in microscale analysis, such as neighborhood or community analysis (Schlossberg 2003; Ashley et al. 2014).

To represent exposure for this study, census population (total count of people) and housing units (total count of occupied or vacant housing units) data were acquired from the National Historical Geographic Information System, version 2.0 (https://www.nhgis.org/). These data were collected at the tract (block) level for every decennial census from 1960 to 2010 (1990–2010). Population and household count projections for 2020–2040 were acquired from Woods and Poole Economics, Inc., at the county level, as well as county-level census data from NHGIS for 1960–2010 (population) and 1980–2010 (households). Using census data, an assumption is made that the people counted are within the enumeration units (blocks or tracts) at all times since census data are essentially a measure of residential population. The data that are collected do not account for temporal differences in population tallies (e.g., increases in local population due to influx of tourists, commuters, mass evacuations, etc.).

To evaluate exposure, rasters were created in a geographic information system for the gridding of population and household data. The grid spacing for tract- and block-level data corresponds to the mean size of each census enumeration during the first year of analysis—i.e., the mean size of all tracts in the five MSAs from 1960 is 17.04 $\text{km}^2$ (4127.87 m × 4127.87 m; Online Resource 1 insert "in ESM"), and the mean size of all blocks in the five MSAs in 1990 is approximately 0.248 $\text{km}^2$ (498.33 × 498.33 m; Online Resource 2 insert "in ESM"). A grid was not created for the county-level population and household data for 2020–2040 due to the assumption of uniform distribution (meaning population is equally distributed throughout the spatial unit); gridding county-level data would not add any more detail than already provided by the county-level data. These grids were overlaid onto the population and household data, and then, these data were reapportioned to the grid using the proportionate allocation method, which overlays a source zone (e.g., blocks) with a target zone (e.g., grid) to transfer data from the source zone to the target zone using proportionate allocation (Deichmann et al. 2001; Ashley et al. 2014). Each grid cell in the target zone is given a value based on the proportion of the source polygon that is located within the grid cell.

## 2.2 Tornado climatology

Data for the tornado climatology construction was acquired from the SPC's SevereGIS (http://www.spc.noaa.gov/gis/svrgis/). All tornado touchdown points rated EF/F1 and greater located in the contiguous USA for 1960 through 2011 were included in the analysis due to the unnatural, inflationary counts of EF/F0 observed during this period (Verbout et al. 2006; Doswell et al. 2009). The tornado point dataset used to create the spatial tornado climatology may suffer from an urban population frequency/magnitude reporting bias (i.e., higher report frequency in comparison with rural locations due to the increased number of storm reporters in urban locations; Anderson et al. 2007; Elsner et al. 2013a, b). These biases promote increased detection for EF/F0 and EF/F1 tornadoes resulting in greater numbers of tornado points around population centers. EF/F1 tornado points were not removed due to the overall consistency of reporting since 1960 of EF/F1 + tornadoes (slope $= -0.35$; Fig. 2).

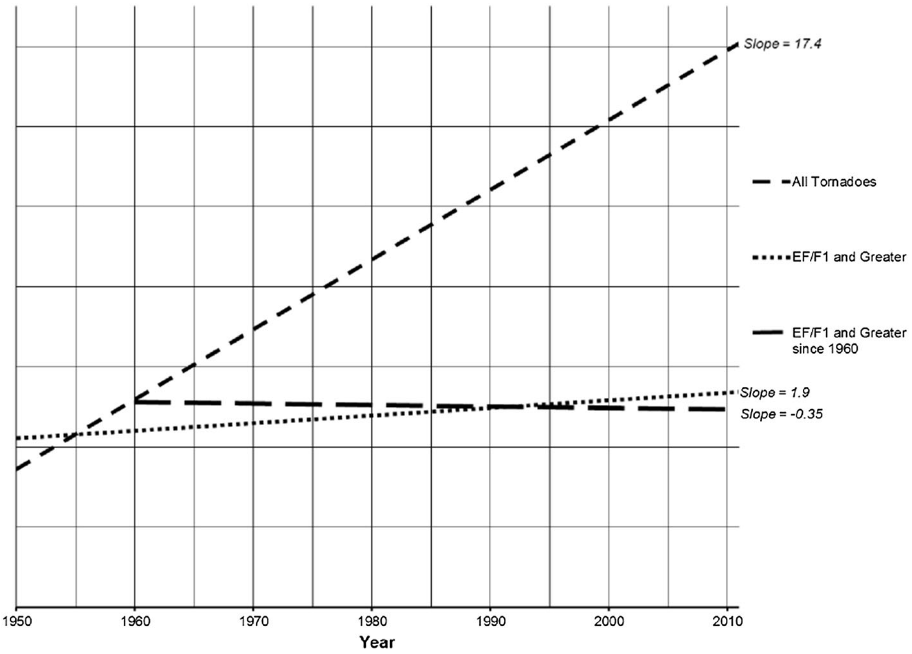

**Fig. 2** Linear trend lines of all tornado reports (1950–2011), EF/F1 + tornado reports (1950–2011), and EF/F1 + tornado reports (1960–2011)

A climatology that represents tornado risk was generated using the Brooks et al. (2003) methodology. A kernel density estimation (KDE) was created across the contiguous USA for all non-EF/F0 tornadoes, all significant (EF/F2+) tornadoes, and all violent (EF/F4–EF/F5) tornadoes. A KDE is used rather than raw count densities because the tornado dataset is noisy due to the small sample size and imprecision in reporting (Brooks et al. 2003). The KDE output is in mean annual tornado days, or the number of days per year at least one tornado occurs. The use of tornado days instead of reports reduces the influence and potential inflation due to large outbreaks, and furthermore, tornado days are steadier over time compared to the raw reports (Brooks et al. 2003).

## 2.3 Tornado scenarios

The tornado climatology and the MSAs exposure changes provide an overall assessment of how the tornado hazard and disaster potential has grown or diminished for the five MSAs. To supplement this perspective, hypothetical tornado paths were used to simulate possible disaster scenarios in each MSA to present a microscale view of how exposure changes have altered the tornado disaster potential from 1960 to 2010 (tract-level analysis from 1960 to 2010 and block-level analysis from 1990 to 2010). The tornado test case, or hypothetical path, for this analysis was derived from the damage attributes of the May 22, 2011, Joplin, MO EF5 tornado (Marshall et al. 2012) and climatological mean width information of contemporary violent tornadoes (Ashley et al. 2014). Following the methodological procedures outlined in Ashley et al. (2014), the hypothetical tornado path was restricted to 10 km long and placed over several different areas of each MSA, representing regions that typify rural, exurban, suburban, and urban developments in 1990. The use of a 10-km-long segment of the hypothetical tornado allows for analysis of specific development types (i.e., rural, exurban, suburban, and urban). The length of the full hypothetical tornado scenario would cross many different types of development areas, restricting the analysis that could be completed. In addition, areas that transitioned from rural to exurban, exurban to suburban, and suburban to urban during the two-decade period 1990–2010 were evaluated. Due to the assumption of constant population temporally (daytime vs. nighttime), scenarios may over- or underestimate the theoretical population affected by a tornado. The number of housing units affected should be a more robust assessment of potential built-environment impacts since these structures are semipermanent.

The 10-km tornado segment was intersected with the gridded exposure data, and subsequently, the population and housing unit data were proportionally allocated to the tornado path segment. Potentially affected population and housing units from each year of analysis and for entire MSAs were compared to determine the change in spatiotemporal, microscale tornado exposure. This microscale investigative approach examines how each MSA's development character during the latter half of the 20th century through the early 21st century has affected its overall potential to tornado disaster.

To assess possible exposure changes into the future, the full-length hypothetical tornado (67.3 km in length) was used with the county-level projection data. The tornado track was overlaid in three different positions in each MSA: northern extent, central, and southern extent. The full-length track, whose dimension was derived based on the climatological mean of contemporary violent events, is used due to the coarseness of the data used (county level). The full-length track allows multiple counties to be sampled at one time. Population and households were proportionally allocated using the same methods for 1960–2040 (1980–2040 for households).

# 3 Results

## 3.1 Exposure

Population in the USA has grown from approximately 180 million people in 1960 to over 308 million people in 2010. Using projections from Woods and Poole Economics, Inc., the population in the USA is expected to expand to over 406 million people by 2040, an increase of 32 % from 2010. The number of housing units in the USA has risen from approximately 68 million to just under 132 million, or 92 %, from 1970 to 2010. The number of households grew approximately 45 % from 1980 to 2010, or from just over 80 million to nearly 117 million, and is projected to grow to 152.5 million, or another 31 %, by 2040. These initial macroscale statistics reveal that an amplifying population, its affiliated developed footprint, and forecasted expansion will logically increase exposure to all geophysical hazards, not just those affiliated with severe storms.

Within the five MSAs assessed, all three variables followed the intensifying exposure pattern found for the country. From 1960 to 2010, Dallas, TX, had the largest magnitude change in population, while Atlanta, GA, had the greatest magnitude changes in households and housing units (Table 1). Projecting out to 2040, Dallas is expected to have the most change in population and Atlanta will have the greatest amplification in households. Collectively, only four counties out of the 80 total counties (based on the 2010 MSA definition) in the five MSAs investigated decreased in population from 1960 to 2010. Of the counties that grew in population within the five MSAs, a majority increased by more than 50 % from 1960 to 2010. Employing the county projections, only five out of 80 counties are expected to lose population by 2040.

**Table 1** Historical and projected changes in population, housing units, and households for the USA and the five MSAs in the study area

| | Historical change | | Projected change | |
|---|---|---|---|---|
| | Start year-2010 Count | Start year-2010 % Change | 2010–40 Count | 2010–40 % Change |
| *USA* | | | | |
| Population (1960) | 129,422,363 | 72.17 | 97,900,997 | 31.71 |
| Housing units (1970) | 63,054,252 | 91.85 | – | – |
| Households (1980) | 36,326,619 | 45.19 | 35,712,430 | 30.60 |
| *Atlanta* | | | | |
| Population | 3,880,675 | 279.55 | 3,368,820 | 63.94 |
| Housing units | 4,045,890 | 76.79 | – | – |
| Households | 1,117,008 | 136.18 | 1,213,201 | 62.63 |
| *Chicago* | | | | |
| Population | 2,465,467 | 34.68 | 2,111,588 | 22.05 |
| Housing units | 1,238,166 | 47.54 | – | – |
| Households | 677,763 | 23.87 | 808,504 | 22.99 |
| *Dallas/Fort Worth* | | | | |
| Population | 4,696,482 | 260.19 | 4,656,068 | 71.62 |
| Housing units | 1,725,046 | 204.98 | – | – |
| Households | 1,235,666 | 110.86 | 1,671,052 | 71.10 |
| *Oklahoma City* | | | | |
| Population | 689,335 | 108.88 | 415,843 | 31.45 |
| Housing units | 294,334 | 107.47 | – | – |
| Households | 170,068 | 49.22 | 144,206 | 27.97 |
| *St. Louis* | | | | |
| Population | 539,423 | 23.99 | 294,205 | 10.55 |
| Housing units | 382,815 | 45.44 | – | – |
| Households | 225,972 | 25.57 | 128,803 | 11.61 |

Start year refers to the year of data the variable was first available, which is 1960 for population, 1970 for housing units, and 1980 for households

To determine whether the population and affiliated housing units are increasing in one area of an MSA or whether there is a sprawling nature to the growth, grid cells were classified as either rural, exurban, suburban, or urban based on the housing unit density classification scheme promoted by Theobald (2005). Mapping the MSAs using the classification scheme (Fig. 3; Online Resource 3 insert “in ESM”) provides a visual representation of the spreading of population and housing, leading to an “expanding bull’s eye effect” defined by Ashley et al. (2014).

All five MSAs experienced increasing total area classified as exurban and suburban, while decreasing in area classified as rural (Table 2). Urban areas in Atlanta, Chicago, and Dallas increased from 1990, though smaller than increases in suburban or exurban areas within the same MSAs. The percentage of area with exurban development in Atlanta is the largest of the five MSAs, suggesting that growth within the Atlanta, GA, MSA has been typified by areas of low-density development rather than high-density development. The expansion of exurban and suburban areas along with the decline in rural areas supports

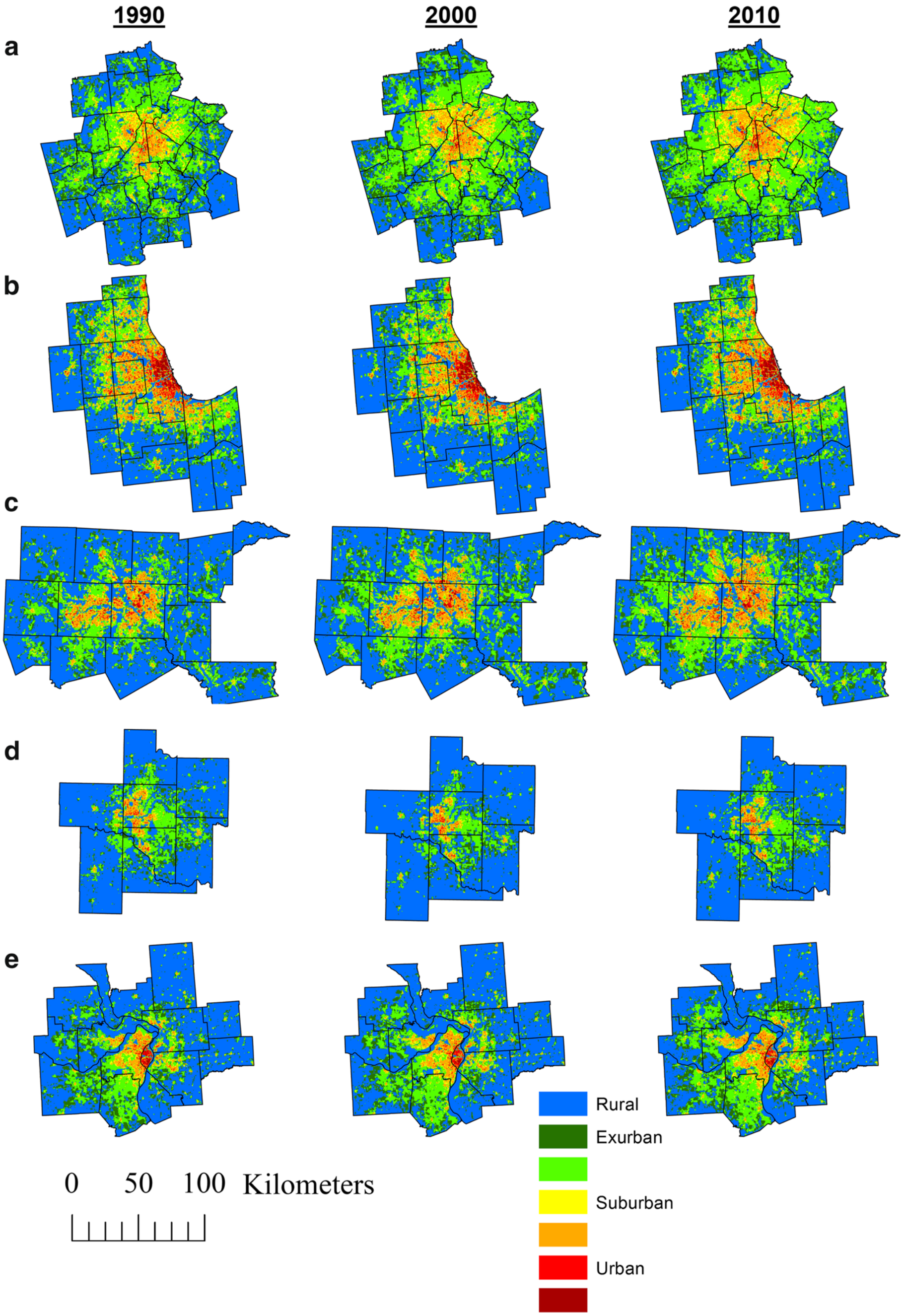

**Fig. 3** Gridded block-level housing unit density in 1990–2010 for **a** Atlanta, **b** Chicago, **c** Dallas, **d** Oklahoma City, and **e** St. Louis

**Table 2** Percentage area covered by urban, suburban, exurban, or rural based on Theobald (2005) definitions for 1990, 2000, and 2010

| | Percentage area covered by classification | | | | Total area (km$^2$) |
|---|---|---|---|---|---|
| | Urban (%) | Suburban (%) | Exurban (%) | Rural (%) | |
| *Atlanta* | | | | | |
| 1990 | 0.56 | 9.84 | 48.63 | 40.96 | 21,968 |
| 2000 | 0.70 | 13.02 | 54.21 | 32.07 | |
| 2010 | 0.97 | 17.85 | 55.28 | 25.90 | |
| *Chicago* | | | | | |
| 1990 | 7.51 | 13.07 | 27.44 | 51.98 | 20,688 |
| 2000 | 8.87 | 15.37 | 27.78 | 47.98 | |
| 2010 | 9.38 | 17.88 | 28.08 | 44.65 | |
| *Dallas* | | | | | |
| 1990 | 1.09 | 7.62 | 27.24 | 64.05 | 27,638 |
| 2000 | 1.29 | 9.11 | 32.89 | 56.72 | |
| 2010 | 1.58 | 11.60 | 37.55 | 49.28 | |
| *Oklahoma City* | | | | | |
| 1990 | 0.43 | 3.42 | 19.56 | 76.59 | 16,513 |
| 2000 | 0.40 | 3.86 | 22.43 | 73.31 | |
| 2010 | 0.45 | 4.39 | 26.07 | 69.10 | |
| *St. Louis* | | | | | |
| 1990 | 0.92 | 6.32 | 27.81 | 64.96 | 20,933 |
| 2000 | 0.88 | 7.16 | 30.44 | 61.52 | |
| 2010 | 0.92 | 8.05 | 32.86 | 58.17 | |
| *All MSAs* | | | | | |
| 1990 | 1.50 | 8.23 | 30.56 | 59.83 | 107,740 |
| 2000 | 1.50 | 9.92 | 34.18 | 54.40 | |
| 2010 | 1.69 | 12.28 | 36.68 | 49.36 | |

previous results revealing that sprawl development is creating greater exposure in more areas (Hall and Ashley 2008; Bouwer 2011; Morss et al. 2011; Paulikas and Ashley 2011; Ashley et al. 2014).

## 3.2 Tornado Risk

In the contiguous USA, 26,172 tornadoes rated EF/F1 or greater were reported from 1960 to 2011; approximately 63 % of those tornadoes were rated EF/F1. The spatial distribution of EF/F1 + tornadoes reveals an area covering most of the Plains and Mississippi Valley that has an expected value of more than 0.75 tornado days per year (Fig. 4a). Maximum areas of greater than 1.25 tornado days per year are located in central Oklahoma and southern Mississippi. The spatial distribution of significant (EF/F2+) tornadoes reveals areas of more than five tornado days per decade in central Oklahoma extending into Texas and in northern Alabama (Fig. 4b). The maximum area of violent (EF/F4 +) tornadoes is located in northern Alabama (>4.5 days per century; Fig. 4c).

When examining the risk within each of the five MSAs studied, expected occurrence ranged from 0.65 tornado days per year (Chicago) to 1.30 tornado days per year

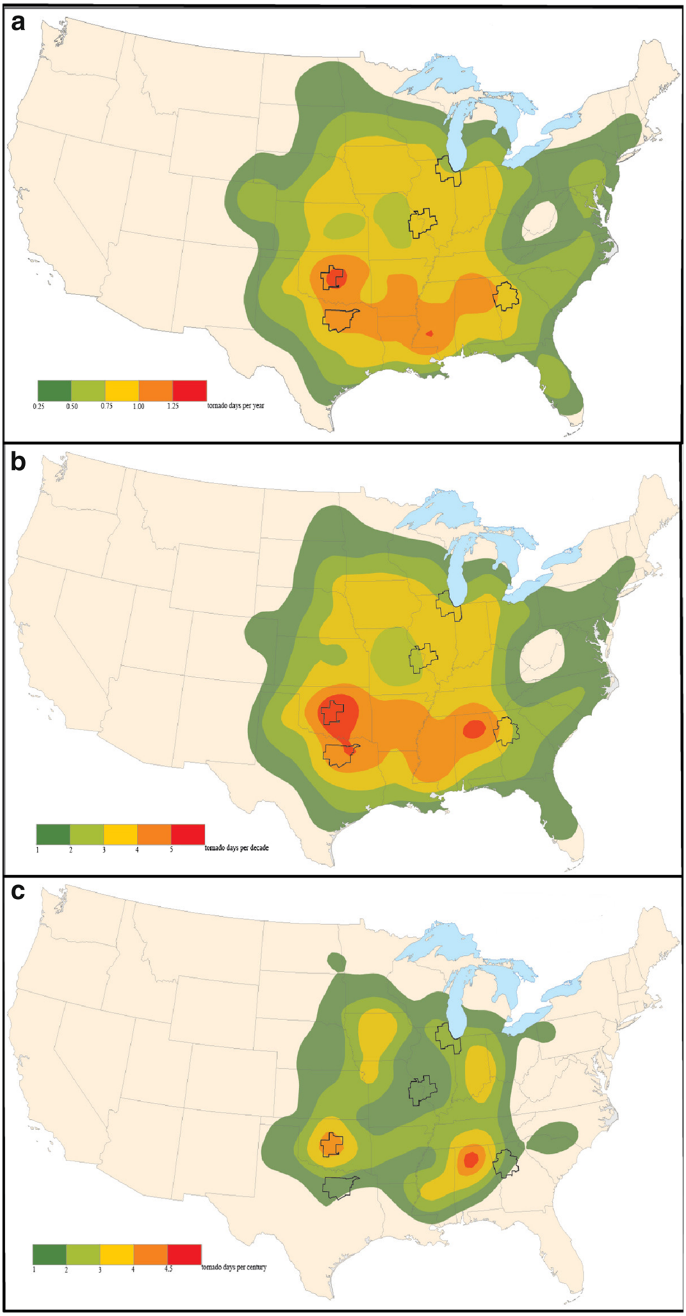

**Fig. 4** Spatial tornado day climatology for **a** EF/F1 + tornadoes (tornado days per year), **b** EF/F2 + tornadoes (tornado days per decade), and **c** EF/F4 + tornadoes (tornado days per century) during the period 1960–2011

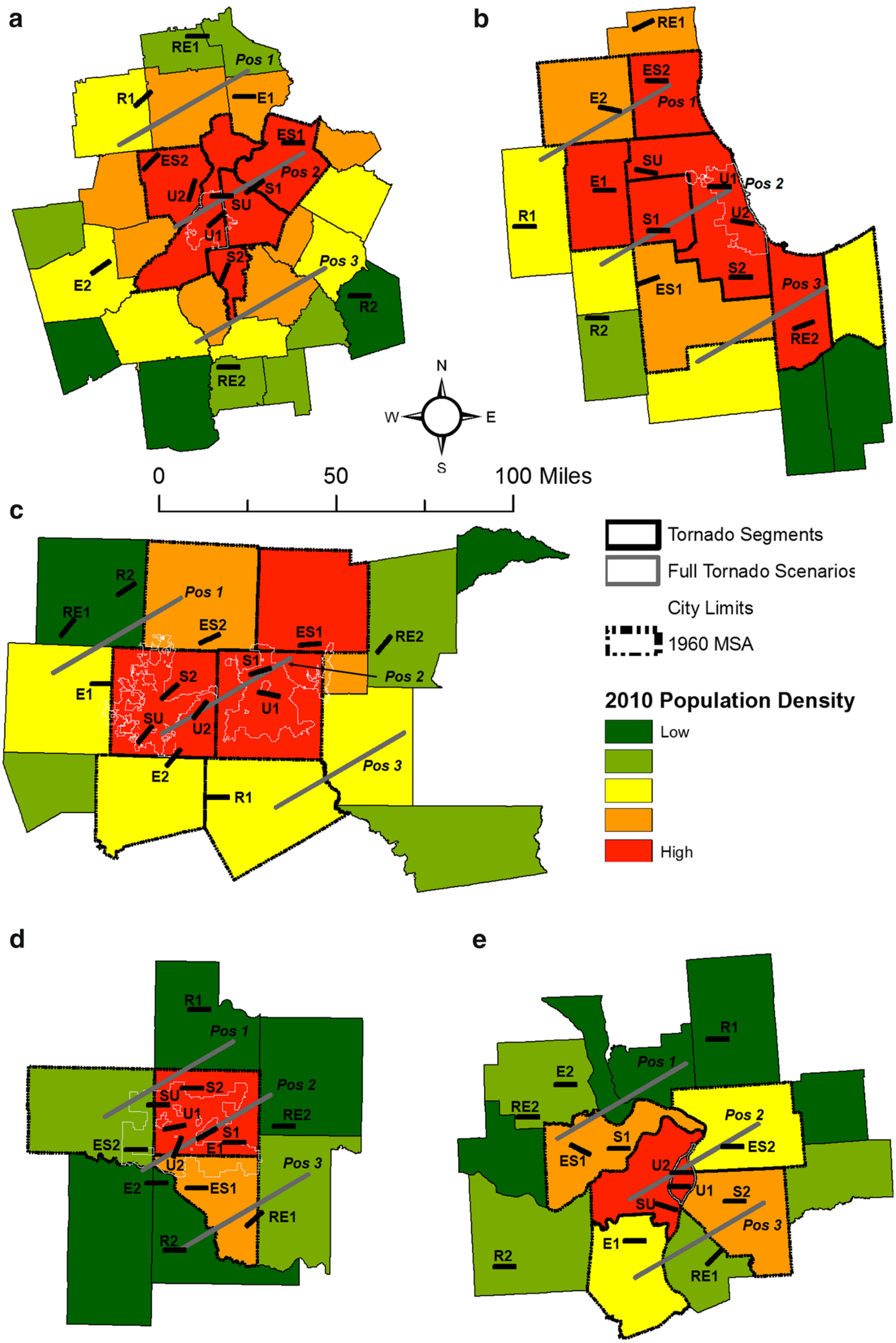

**Fig. 5** Tornado scenario placement for the 10-km track segments (*black*) and full-length county-level tracks (*gray*) overlaid on relative 2010 county population density for **a** Atlanta, **b** Chicago, **c** Dallas/Fort Worth, **d** Oklahoma City, and **e** St. Louis

**Table 3** Affected population and housing units for block and tract-level data for the urban tornado segments (cf. Fig. 5)

| Years | Urban tornado scenarios | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Urban 1 | | | | Urban 2 | | | |
| | Population | | Housing units | | Population | | Housing units | |
| | Block | Tract | Block | Tract | Block | Tract | Block | Tract |
| *Atlanta, GA* | | | | | | | | |
| 1960 | – | 47,369 | – | 17,853 | – | 4459 | – | 1308 |
| 1970 | – | 36,911 | – | 14,053 | – | 8014 | – | 2540 |
| 1980 | – | 28,102 | – | 13,057 | – | 10,532 | – | 4845 |
| 1990 | 35,966 | 26,299 | 18,461 | 13,130 | 21,155 | 14,473 | 12,767 | 8152 |
| 2000 | 36,885 | 30,016 | 18,964 | 14,363 | 24,921 | 16,930 | 12,613 | 8226 |
| 2010 | 39,501 | 33,321 | 21,418 | 18,776 | 23,836 | 16,994 | 13,203 | 9004 |
| Percentage change | 10 % | −30 % | 16 % | 5 % | 13 % | 281 % | 3 % | 589 % |
| *Chicago, IL* | | | | | | | | |
| 1960 | – | 89,441 | – | 31,600 | – | 129,007 | – | 47,620 |
| 1970 | – | 84,828 | – | 31,263 | – | 115,410 | – | 40,426 |
| 1980 | – | 78,805 | – | 32,023 | – | 94,888 | – | 35,034 |
| 1990 | 97,062 | 79,306 | 37,051 | 31,316 | 76,466 | 81,931 | 28,191 | 30,906 |
| 2000 | 116,801 | 92,857 | 38,902 | 32,938 | 77,252 | 79,956 | 26,770 | 28,562 |
| 2010 | 110,368 | 88,198 | 39,715 | 33,560 | 67,104 | 68,704 | 26,181 | 28,006 |
| Percentage change | 14 % | −1 % | 7 % | 6 % | −12 % | −47 % | −7 % | −41 % |
| *Dallas/Fort Worth, TX* | | | | | | | | |
| 1960 | – | 34,458 | – | 16,586 | – | 5682 | – | 1856 |
| 1970 | – | 31,412 | – | 14,631 | – | 11,184 | – | 3,794 |
| 1980 | – | 27,210 | – | 13,503 | – | 14,763 | – | 6379 |
| 1990 | 48,399 | 27,197 | 26,210 | 13,393 | 23,244 | 21,766 | 11,900 | 10,596 |
| 2000 | 56,921 | 32,074 | 26,291 | 14,482 | 26,903 | 24,979 | 12,627 | 11,103 |
| 2010 | 50,113 | 32,543 | 29,542 | 18,279 | 25,347 | 22,032 | 13,132 | 10,741 |
| Percentage change | 4 % | −6 % | 13 % | 10 % | 9 % | 288 % | 10 % | 479 % |
| *Oklahoma City, OK* | | | | | | | | |
| 1960 | – | 26,726 | – | 11,849 | – | 15,449 | – | 5244 |
| 1970 | – | 25,734 | – | 11,256 | – | 20,875 | – | 7052 |
| 1980 | – | 22,934 | – | 11,672 | – | 20,428 | – | 8501 |
| 1990 | 23,993 | 20,463 | 14,117 | 11,231 | 24,297 | 20,765 | 11,642 | 9508 |
| 2000 | 26,644 | 22,014 | 13,854 | 10,828 | 27,114 | 22,523 | 11,569 | 9564 |
| 2010 | 27,150 | 22,366 | 13,386 | 10,598 | 29,476 | 24,651 | 11,798 | 9804 |
| Percentage change | 13 % | −16 % | −5 % | −11 % | 21 % | 60 % | 1 % | 87 % |
| *St. Louis, MO* | | | | | | | | |
| 1960 | – | 65,301 | – | 25,181 | – | 68,587 | – | 27,639 |
| 1970 | – | 53,297 | – | 21,071 | – | 55,650 | – | 21,138 |
| 1980 | – | 40,594 | – | 19,122 | – | 37,365 | – | 16,614 |
| 1990 | 44,058 | 37,128 | 21,974 | 18,824 | 48,367 | 31,818 | 22,359 | 15,583 |
| 2000 | 40,652 | 35,080 | 20,601 | 17,689 | 34,906 | 25,890 | 17,990 | 13,447 |

**Table 3** continued

| Years | Urban tornado scenarios | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Urban 1 | | | | Urban 2 | | | |
| | Population | | Housing units | | Population | | Housing units | |
| | Block | Tract | Block | Tract | Block | Tract | Block | Tract |
| 2010 | 35,729 | 31,452 | 20,243 | 17,540 | 28,520 | 24,695 | 16,711 | 13,647 |
| Percentage change | −41 % | −19 % | −8 % | −30 % | −52 % | −64 % | −25 % | −51 % |

(Oklahoma City). Chicago and St. Louis have the least risk to EF/F1 + tornadoes (<0.9 tornado days per year), while Oklahoma City has the greatest risk to EF/F1 + tornadoes (>1.15 tornado days per year).

## 3.3 Tornado scenarios

To assess the microscale changes in tornado exposure, an observationally derived, 10-km hypothetical tornado segment was transposed across the five MSAs for 13 different scenario locations. Segment placement in the block-level data analysis focused on development character types (two each in urban, suburban, exurban, and rural areas, as classified in 1990) and transition zones that were determined using a kernel density estimation of grid cells (not shown) that changed from rural to exurban (two locations), exurban to suburban (two), and suburban to urban (one) from 1990 to 2010.

Of the 65 total tornado segment placements (13 positions in each of the five MSAs; Fig. 5) in the five MSAs using gridded block-level data, only seven had decreases in affected population and six had decreases in affected housing units from 1990 to 2010 (Online Resource 4–8). Of those scenarios that decreased, St. Louis had four hypothetical tornado segments affect less population (Urban 1, Urban 2, Suburban 2, and Suburban to Urban transition) with both urban positions also affecting fewer housing units. All other tornado segment placements affected more population and housing units in 2010 than in 1990. Of the 13 segments in each MSA, Atlanta had the greatest magnitude change (>41,000) in affected population and St. Louis had a decrease in overall affected population from 1990 to 2010. The decrease found in St. Louis can be attributed to the two urban scenarios affecting approximately 28,000 fewer people. Atlanta also experienced the greatest increase in affected housing units, while St. Louis decreased in housing units affected. The greatest potential for population to be affected of all the tornado segment positions was the Urban 1 position in Chicago (110,367 people in 2010; Table 3). A tornado that could potentially occur in the urban area of any of the five MSAs would have the greatest impact in Chicago, which supports findings from Wurman et al. (2007) in their comparison with tornado tracks traversing different cities' urban cores.

Tornado segments were then placed in the same positions for the gridded tract-level data. The only segments that were used from the original 13 positions were the scenarios that were located within the counties that were considered a part of the 1960 MSA definition. All urban and suburban positions were used, as well as all exurban to suburban and suburban to urban transition zone tornado segments.

For the longer period 1960–2010, the changes in affected population and housing units for the tornado segment scenarios are variable (Online Resource 4–8). Of the ten urban positions, seven had decreased in affected population during the five-decade period (Table 3). The greatest change in affected population was the Urban 2 position in Chicago, which was located in the southern portion of the city of Chicago. This position had a decrease of 60,000 people from 1960 to 2010, causing the total five-decade magnitude change for the Chicago MSA to rank fourth out of the five MSAs in the study. The Urban 2 position in Chicago had the greatest magnitude of affected people (129,007 people); however, that was in 1960 and not 2010. These results (in conjunction with the block-level path results) complement other research that revealed parts of the urban cores of some US cities (e.g., St. Louis and Chicago) have lost population (Beauregard 2009; Greene and Pick 2012; Ashley et al. 2014).

In the case of the southern portion of the Chicago city limits (Urban 2 position), population loss can be attributed to the housing policy by the city government (Hagedorn and Rauch 2007) and the suburbanization of the population to the outer edges of the city (Greene and Pick 2012); specifically, the destruction of public housing (e.g., the Robert Taylor Homes) and a trend of outward migration of the middle class displaced thousands of minority residents from the South Side of Chicago. The Urban 2 position traversed through the community area of Englewood, Chicago. Englewood peaked in population in 1960 at over 97,000 and has decreased every decade thereafter due to dramatic housing stock loss and the inability to attract businesses to the area (Chicago Historical Society 2005).

Due to the difference in the block- and tract-level enumeration units and the two grid resolution sizes, the affected population and housing units for the same tornado tracks are divergent. Through the proportionate allocation in the gridding of census data and the intersecting of the tornado tracks, the assumption of uniform distribution causes discrepancies in how an area is represented. Using a percentage difference measure between the block- and tract-affected populations, areas that are less populated (exurban/rural, rural to exurban/exurban to suburban transition zones) had the highest percentage differences, some over 100 %. Block-level data resulted in greater numbers of affected population and housing units compared to tract-level data 75 % of the time. The differences between the affected population and housing units in tract paths and the block paths suggest that the modifiable areal unit problem (MAUP; Openshaw 1984) is present. MAUP occurs when different levels of spatial aggregation of the same data cause differing results. In this study, the differing data resolutions (block level vs. tract level) produce conflicting results for the same areas. In this situation, the highest-resolution data available should be employed (Schlossberg 2003; Ashley et al. 2014) to create the most detailed results.

To assess possible future tornado scenarios, a full-length hypothetical tornado track was superimposed three times across each MSA (Fig. 5). The hypothetical tornado track was created using mean length and width attributes of historical EF/F5 tornadoes from 1995 to 2011; the mean length (width) is 67.3 km (1.39 km). The use of a full-length tornado track instead of the 10-km segment in this particular analysis is due to the relatively coarse resolution of the county projection data. The tornado tracks were angled from the west-southwest to the east-northeast, which represents the most common direction of tornadoes in the USA (Suckling and Ashley 2006). Positions were chosen to sample the northern extent, center, and southern extent of each MSA. Due to the assumption of uniform distribution, the proportionate allocation process using county-level data likely over- or underestimates the number of affected people and households, depending on the area the tornado track traverses. However, broad trends in the data (increase/decrease in magnitude) are assumed to be reflective of the potential scenarios.

Of the 15 different full-length positions assessed, only the hypothetical tornado track that traversed the urban core in St. Louis (Pos 2; Fig. 5e) decreased in affected population

**Table 4** Affected population (P) and households (HH) for county-level data for the full-length tornado disaster scenarios (cf. Fig. 5)

| | | Historical | | | Projected | | |
|---|---|---|---|---|---|---|---|
| | | 1960 | 2010 | 1960–2010 % change | 2020 | 2040 | 2010–2040 % change |
| *Atlanta* | | | | | | | |
| Pos 1 | P | 1898 | 15,271 | 705 | 19,654 | 28,692 | 88 |
| | HH | – | 5383 | 330 | 7172 | 10,099 | 88 |
| Pos 2 | P | 19,288 | 70,869 | 87 | 85,898 | 116,063 | 64 |
| | HH | – | 26,221 | 127 | 32,833 | 42,735 | 63 |
| Pos 3 | P | 2295 | 19,933 | 136 | 28,302 | 45,951 | 131 |
| | HH | – | 6,943 | 352 | 10,177 | 15,823 | 128 |
| *Chicago* | | | | | | | |
| Pos 1 | P | 10,030 | 27,080 | 170 | 31,405 | 41,074 | 52 |
| | HH | – | 9418 | 87 | 11,379 | 14,616 | 55 |
| Pos 2 | P | 74,450 | 107,310 | 31 | 114,666 | 130,256 | 21 |
| | HH | – | 39,965 | 23 | 44,335 | 49,158 | 23 |
| Pos 3 | P | 19,414 | 26,254 | 136 | 28,398 | 33,217 | 27 |
| | HH | – | 9479 | 31 | 10,592 | 11,976 | 26 |
| *Dallas/Fort Worth* | | | | | | | |
| Pos 1 | P | 1093 | 9882 | 804 | 13,188 | 19,878 | 101 |
| | HH | – | 3573 | 296 | 4934 | 7175 | 101 |
| Pos 2 | P | 31,301 | 86,026 | 72 | 100,696 | 129,894 | 51 |
| | HH | – | 31,150 | 66 | 37,717 | 47,035 | 51 |
| Pos 3 | P | 1475 | 5090 | 136 | 6377 | 9025 | 77 |
| | HH | – | 1720 | 161 | 2240 | 3092 | 80 |
| *Oklahoma City* | | | | | | | |
| Pos 1 | P | 6086 | 11,347 | 86 | 12,722 | 15,258 | 34 |
| | HH | – | 4454 | 41 | 5,110 | 5811 | 30 |
| Pos 2 | P | 16,278 | 28,068 | 46 | 30,017 | 33,334 | 19 |
| | HH | – | 11,194 | 34 | 12,249 | 12,853 | 15 |
| Pos 3 | P | 2018 | 7443 | 136 | 8349 | 10,042 | 35 |
| | HH | – | 2840 | 91 | 3277 | 3767 | 33 |
| *St. Louis* | | | | | | | |
| Pos 1 | P | 2073 | 8811 | 325 | 9934 | 12,252 | 39 |
| | HH | – | 3299 | 143 | 3867 | 4662 | 41 |
| Pos 2 | P | 81,204 | 55,357 | −45 | 53,793 | 50,984 | −8 |
| | HH | – | 23,400 | −4 | 23,492 | 21,436 | −8 |
| Pos 3 | P | 7586 | 10,211 | 136 | 10,685 | 11,736 | 15 |
| | HH | – | 3923 | 32 | 4288 | 4662 | 19 |

and households from 1960 to 2010 and is projected to continue to affect less people in the future (Table 4). This decrease in affected population and households reaffirms that there are cases in the USA where urban core population loss has actually reduced overall human exposure; this result was found in the previous block- and tract-level scenarios, as well.

The greatest increases in affected population and housing units were the tornado tracks that were overlaid on the urban areas (Pos 2; Fig. 5a, c) in Atlanta and Dallas. Tornado track Pos 2 in Atlanta (Fulton, DeKalb, and Gwinnett counties) affected over 51,000 more people in 2010 than in 1960 and would affect over 45,000 more in 2040 than in 2010. Tornado track Pos 2 in Dallas (Tarrant County and Dallas County) affected over 54,000 more people in 2010 than in 1960 and over 43,000 more people in 2040 than in 2010. Affected households had similar patterns to affected population.

## 4 Discussion and conclusion

The goal of this study was to examine the spatiotemporal trends of exposure to tornadoes within five MSAs in the USA through a gridded framework. Results reveal growth in population and housing units within the USA and within each MSA investigated. Those trends of growth are forecasted to continue in the future, creating greater exposure to geophysical hazards such as tornadoes. Of the five MSAs studied, the greatest relative increases were in Atlanta and Dallas, while Chicago and St. Louis had the smallest relative increases. All five MSAs had growth outwards from the urban cores, creating new areas of people and housing that could be affected by all facets of severe storm hazards.

Due to growing exposure and its location in regions with relatively high risk for tornadoes, Dallas, TX, has the greatest potential for tornado disaster occurrence of the MSAs studied. Oklahoma City has a higher risk for tornado occurrence; however, the exposure of Oklahoma City is not as great as Dallas due to the relative population sizes. This difference is supported within the hypothetical tornado scenario statistics, as Dallas scenarios affected more people and housing units than the scenarios in Oklahoma City. Chicago has more population and housing units than Dallas, though the tornado risk is the lowest of the MSAs investigated.

Based on the results from this study and others (Changnon 2003; Changnon and Burroughs 2003; Hall and Ashley 2008; Paulikas and Ashley 2011; Shepherd et al. 2011; Bouwer 2013; Ashley et al. 2014), exposure can be seen as a driving force in the increasing impacts to humans from severe weather. The “expanding bull’s eye effect” (Ashley et al. 2014) provides a conceptual model of the increasing exposure within metropolitan areas to hazard occurrence. Essentially, larger areas of metropolitan regions are becoming exurban and suburban, implying that more people and their housing units are in the path of severe weather. Projected exposure changes illustrated in this study support research (e.g., Bouwer 2013) that discovered that swelling human and built-environment exposure will continue to be as great (if not, greater) an influence on disaster loss trends as the potential change in frequency/magnitude of hazards in a warming world.

Potential disaster scenarios that declined in population and housing units (mostly urban scenarios) do not lead to those scenarios being less exposed than others, as the urban scenarios still affected the most people within each MSA. The declines (especially within St. Louis and Chicago) in the urban scenarios illustrate the diminishing population within urban cities (Beauregard 2009), even though the surrounding areas may be increasing as metropolitan areas have grown (Short 2012). This decline could be due to the net migration patterns from metropolitan areas to nonmetropolitan areas or the movement of residents in central cities to locations outside of the central cities (Schachter et al. 2003). The urban decline that has occurred suggests that the magnitude of the center of the “expanding bull’s eye” has decreased in terms of population. However, this does not suggest that those areas are less vulnerable to hazards because there is possible heightened susceptibility and reduction in coping capacity (e.g., older populations living alone, decrepit housing conditions, or poverty; e.g., see Klinenberg (2002)). The existing built environment and infrastructure are also still present, resulting in a notable target for severe weather hazards to affect.

Future vulnerability research should examine exposure alongside more complex vulnerability constituents of susceptibility and adaptive capacity to reveal a more complete picture of the character of the expanding bull's eye effect. For example, socioeconomic variables could be used to determine social vulnerability (Cutter et al. 2003). The social vulnerability and affiliated capacity of the various MSAs would permit a continued assessment of the overall potential for tornado hazard occurrence. The types of buildings in various areas within each MSA could be used to determine probabilities of destruction or survivability in potential tornado disaster scenarios (Wurman et al. 2007). Another avenue of research would be the creation of a single metric that would use multiple variables to determine the vulnerability of a place (Cutter et al. 2003; Boruff et al. 2003; Borden et al. 2007; Peduzzi et al. 2009; Flanagan et al. 2011). Through the use of a gridded framework similar to that implemented in this study, research examining the estimation of small-scale indices could assist with mitigation efforts within communities and neighborhoods.

The use of various socioeconomic variables would also lend to investigations of why the various growth patterns discovered in this study occurred (e.g., evaluate reasons for why growth occurred more in Missouri rather than Illinois within the St. Louis MSA). These growth patterns could be due to physical reasons, such as landscape amenities, or due to differences in policies of the various governments (local or state). Investigation into the income of the population, or even the use of crime statistics, in various areas could facilitate an explanation for the decline or increase found in specific locations. Immigration and migration patterns of ethnic or racial groups can engender different population dynamics within cities or urban areas (Greene and Pick 2012)—e.g., the infusion of Hispanic and Latino populations in Chicago within the 2000s. Some growth patterns could be due to education level of the populace and access to highways, as in Atlanta's growth to the northeast of the urban core (Gong and Wheeler 2002).

Employing a gridded framework instead of census enumeration units (blocks/tracts) was successful in the mitigation of the spatial unit variation problem; however, results were still influenced by MAUP. The differences between gridded block-level and tract-level data in the estimation of potentially affected population and housing units by the same tornado segments illustrated the effect of different areal unit sizes on results. The resolution of tract-size data and the grid applied could produce values within the tornado tracks that were incongruent due to the uniform distribution assumption. Due to the small size of the area being sampled by the tornado tracks ($\sim 14\ \mathrm{km}^2$), the use of highest-resolution data available is desirable (Schlossberg 2003; Ashley et al. 2014).

In comparison with previous macroscale research on exposure (Wurman et al. 2007; Hall and Ashley 2008; Paulikas and Ashley 2011; Morss et al. 2011; Bouwer 2013; Ashley et al. 2014), this research promoted a spatially detailed examination of exposure changes across complex and continually evolving urban landscapes. The results suggest that, while there is generally macroscale expansion in development, the spatiotemporal trends at the microscale are multifaceted and in a continual state of flux. The investigation revealed areas that are more vulnerable or less vulnerable to hazards within an urban area, which are not necessarily highlighted in macroscale research.

Events such as the April 27–28, 2011, tornado outbreak, May 22, 2011, Joplin, MO EF5 tornado, and May 20, 2013, Moore, OK EF5 tornado demonstrate explicitly the necessity of additional vulnerability research and the heighted demand for communication between hazard scientists and the public. This study presented (1) a methodological framework and conceptual model to further hazard vulnerability research, (2) identified areas of concern for tornado disaster occurrence within a wide range of relatively high-risk MSAs, (3) created spatial mean annual tornado day climatologies, and (4) illustrated historical and future population and housing growth for MSAs that are frequently impacted by a variety of weather and climate hazards. The discovered spatiotemporal trends of tornado exposure will assist policy makers, hazard scientists, and the public by illustrating the role amplifying exposure has on the increasing tornado impacts.

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