

## SPATIOTEMPORAL CHANGES IN TORNADO HAZARD EXPOSURE: THE CASE OF THE EXPANDING BULL'S EYE EFFECT IN CHICAGO, IL

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### 1. INTRODUCTION

Over the past 80 years—the life span of an average American—the U.S. has more than doubled its population, transitioned from a rural to urban development character, and effectively escalated the exposure of its population and built environment to weather hazards. Exposure to weather extremes contains components of both vulnerability and weather hazard risk and, broadly, is the characteristics of the natural and/or built environment that position a system to be affected by a hazard (Morss et al. 2011). Human and engineered structure exposure has amplified rapidly throughout the U.S. and is arguably one of the primary drivers of increases in disaster frequency and consequences. Urban regions have continually outpaced overall national growth (Census Bureau 2012a), illustrating that weather hazard exposure landscape is not uniform or fixed, but rather focused in specific areas and continually evolving.

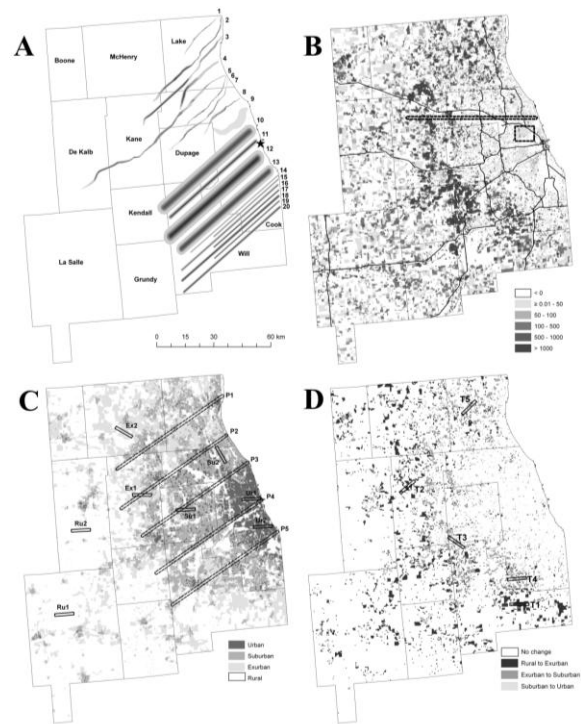
The Chicago, IL metropolitan area is a prime example of the enormous growth that American cities have witnessed during the 20th and early 21st centuries (Auch et al. 2004, Greene and Pick 2011). The Chicago region is characterized by a dense urban core and has experienced extensive, spatially fragmented suburban and exurban growth (Theobald 2005, Green and Pick 2013), or sprawl (Duany et al. 2000, Gilham 2002, Hall and Ashley 2008), during the last 60 years. To what extent has the growth of Chicago population and households increased exposure to weather hazards? To what degree have demographic shifts and transformations in Chicago's developed landscapes, such as that created by sprawl, led to a greater potential for a weather disasters? We assess these questions by 1) employing historical census data in a gridded framework and 2) using a portfolio of significant contemporary and synthetic tornado paths to produce a set of tornado disaster scenarios. Together, these methods are used to evaluate changes in potential tornado hazard impacts on the metropolitan Chicago population and its housing.

### 2. DATA AND METHODOLOGY

#### a. Population and housing grid construction

Initially, Census block boundary information for 1990, 2000, and 2010 were acquired from the University of Minnesota's National Historical Geographic Information System (NHGIS). 1990 is chosen as the initial year

since this was the first census where the block unit—the smallest geographic entity for which the Census Bureau presents data—was available. We evaluate 11 counties (Table 1, Figure 1) in the northeast Illinois region; these counties were chosen to represent the full spectrum of development character found in the area. A grid resolution of 0.16 km<sup>2</sup> was used for the AW procedure at the block-level; this resolution represents the mean size of all blocks in the region for 1990, which is the initial time stamp of analysis and the coarsest of the three analysis iterations.



**Figure 1.** The A) Chicago-area counties under investigation in this research with historical and synthetic tracks placed across the study area. The tornado paths and numeral labels correspond to the track information found in Table 2. The B) percentage change in population from 1990 to 2010 for each 0.16 km<sup>2</sup> grid cell, with 10-km long tornado segment and scenario path S2 placed across northern Kane and Cook Counties. The C) 2010 land-use classification based on Theobald (2005) housing density criteria, with five full-length scenario (S2) paths placed across the developed core of the study area. Eight 10-km long S2 segments – two for each land-use type – are also placed on the map, with Ru corresponding to rural, Ex to exurban, Su to suburban, and Ur to urban. The D) land-use change for the study area from 1990 to 2010 for three transformations assessed; white cells indicate no change or, less common, reversal of land-use. Five 10-km S2 segments are placed across areas that experienced notable land-use transformation, with T1 and T2 assessing rural to exurban change and T3, T4, and T5 evaluating exurban to suburban change.

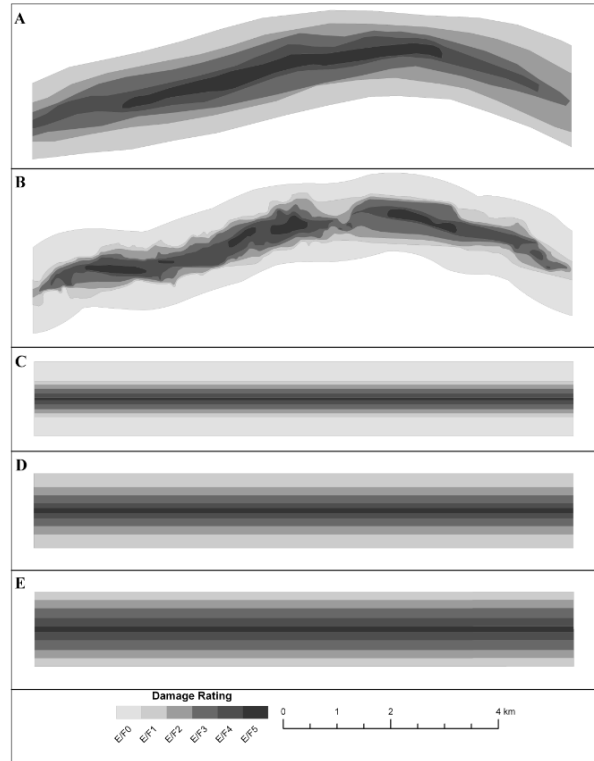
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In constructing the grids in the GIS, a “fishnet” at each resolution was constructed for the area of interest on an Albers equal-area conic projection. Population and housing counts at the block level were transformed from their native irregular geographic units by proportionally allocating to the grid. If a hypothetical grid cell contains 50% of the area of one census block and 20% of the area of a second census block, the housing count for that grid cell will be 50% of the housing count of the first census block and 20% of the housing count of the second census block (SEDAC 2011).

*b. Historical and synthetic tornado tracks*

Since 1950, long-track, significant ( $\geq 8$  km and  $\geq$ EF2) tornadoes have produced 85% of fatalities and 75% of reported damage; infrequent violent ( $\geq$ EF4) events have been the cause of over two-thirds of all tornado deaths (Ashley 2007, Simmons and Sutter 2011). Thus, in scenario-based research and in resulting mitigation actions, it is imperative to focus on these relatively rare events. Initially we gathered GIS-ready tornado paths that contain damage attribute information (Fujita (F) or Enhanced Fujita (EF) scale; Doswell et al. 2009) for contemporary, high-end tornado events (Table 2). In addition, we constructed two sets of synthetic paths that included: 1) parameters and track widths constructed from 3 May 1999 mobile Doppler radar data and post-event analysis (cf. WUR) and 2) mean length and width dimensions of recorded violent (EF4 and EF5) tornadoes from 1995-2011 (Table 3) in conjunction with the percentage area of each EF-scale damage class swept out by the 22 May 2011 Joplin, MO tornado.

The Joplin tornado is the prototypical tornado case to employ in our synthetic research since it: 1) was the deadliest (158 direct fatalities) U.S. tornado since 1947 and 2) is a contemporary representation of a catastrophic tornado scenario in a densely settled area. In constructing our synthetics, we used two sources of damage path information from the Joplin event: 1) the NWS’s assessment and 2) aerial and structure-by-structure ground surveys conducted by Marshall et al. (2012). Dual damage path sources were used to illustrate and evaluate the differences in findings that can be found by two surveys of the same event (Figure 2). In both cases, we focused specifically on the 10-km portion of the track that went through the settled areas of Joplin as this is most representative of a tornado striking a developed region. Since the damage isopleths in the NWS and Marshall et al. (2012) surveys were EF1+, we constructed an EF0 contour to represent the totality of the tornado that was based on the tornado width officially reported in NOAA’s *Storm Data* (i.e., 1463 m). We fit this contour to the Marshall et al. path since this will be our primary synthetic path tool of assessment. The area swept out by each damage class was then converted to a percentage of the total 10-km track segment (Table 4) to promote synthetic tornado path construction (Figure 2).



**Figure 2.** Panel A illustrates the NWS survey assessment for the 2011 Joplin EF5 tornado; panel B indicates the Marshall et al. survey assessment for the Joplin tornado; panel C represents the Synthetic 2 (EF0-EF5) tornado path based on the Marshall et al. Joplin survey and 1995-2011 mean tornado path length/width; panel D indicates the Synthetic 6 (EF1-EF5) tornado path based on the NWS Joplin Survey and 1995-2011 mean tornado path length/width; panel E illustrates Synthetic 4 (EF1-EF5) tornado path based on the Marshall et al. Joplin survey and 1995-2011 mean tornado path length/width.

*c. Path and grid intersect*

To evaluate changes in tornado exposure and assess “worst-case” (Clarke 2005) tornado scenarios for Chicago, we conflated the exposure attribute grids with our tornado path portfolio in a GIS. In this step, we used the underlying census attribute grid (population or housing unit) and placed a single tornado path, or path segment, over a desired location. Path placement was not random; the paths were placed purposely over areas to evaluate how changing development patterns influence the potential tornado disaster landscape. As in Hall and Ashley (2008), we assess specifically areas that have experienced a considerable increase in development due to sprawl. Similar to Rae and Stefkovich (2000) and WUR, but using both temporal and spatial perspectives, we evaluate how the evolving demographics of urban cores have influenced worst-case scenarios. Finally, we examine changes in rural and exurban development characteristics in the Chicago region. The goal of this analysis was not to produce a comprehensive inventory of all possible scenarios for the area; rather, we focus on specific development characters and changes in those landscapes to reveal

how disaster consequences may be amplified by exposure.

Once the path is overlaid on the exposure attribute grid, we “intersect” the demographic grid and tornado path layers in the GIS to combine the geospatial data into a single layer that retains both field and boundary data. Thereafter, we used a “dissolve” tool to generate attributes for each year considered (e.g., population affected by a specific damage rating for scenario in 1990) that may be used in subsequent analysis. Along the edges of the tornado and EF classes, where the track/classes will transect only parts of a grid cell, we use the AW procedure to adjust tallies of population and/or housing based on the fraction of the grid cell impacted.

The scenario tallies of affected people are estimates based on places of residence, since census population data are based on number of residents in an enumeration area. While the number of people affected may vary depending on the situation, the number of housing units impacted should be a relatively robust marker for assessing spatiotemporal changes in disaster potential landscape.

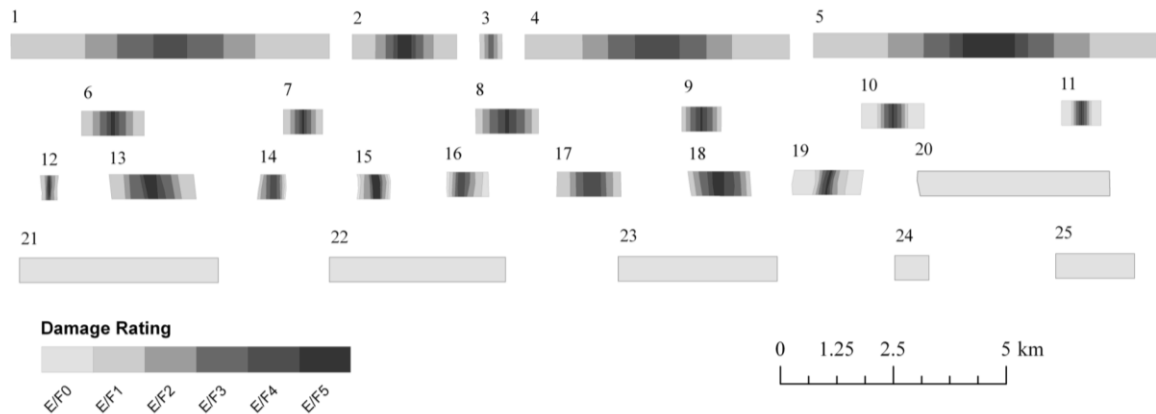
### 3. RESULTS

#### a. Comparison of path attributes

Of the roughly 1500 tornadoes that occur each year in the U.S., less than 0.6% (or approximately 9 yr<sup>-1</sup>) are rated violent (Table 3). While intensity (as inferred by Enhanced Fujita scale) of tornadoes cannot be correlated explicitly with length or width, there is evidence that, generally, both path length and width tend to increase with increasing F/EF-scale (Brooks 2004). The mean length (width) of violent tornadoes is much longer (wider) than all tornadoes as well as significant tornadoes (Table 3). The mean area

theoretically swept out (length x maximum width) by a violent tornado is 39.46 km<sup>2</sup>, whereas tornadoes across all (significant) damage classes were a modest 0.51 km<sup>2</sup> (6.74 km<sup>2</sup>). Therefore, based on contemporary tornadoes, violent events have theoretical damage footprints that are over five times the size of all significant tornadoes and nearly 80 times the size of all documented tornadoes. Logically, the larger the area swept out by the core flow of a tornado, the greater the likelihood that casualties and damage to the built environment will occur.

There were 144 recorded tornadoes from January 1950 to June 2012 with path widths greater than 1.76 km (1 mi) with only three events reported wider than 3.5 km (2 mi), including: 22 May 2004 Hallam, NE F4 (4.4 km, 2.5 mi; McCarthy and Schaefer 2005); 4 May 2007 Hopewell, KS EF3 (3.9 km, 2.2 mi; Lemon and Umscheid 2008); and 7 June 2008 Pardeeville-Cambria, WI EF2 (3.52 km, 2 mi) (Figure 3). Two Oklahoma tornadoes in May 2013 provide additional, contemporary evidence of extremely wide cases. The Newcastle-Moore, OK tornado of 20 May 2013 was over 1.7 km wide and the El Reno, OK tornado of 30 May 2013 was assessed at nearly 4.2 km wide, surpassing the 2004 Hallam, NE as the widest tornado recorded. The mean width of contemporary significant (violent) tornadoes is less than 0.4 km (0.9 km) illustrating that the synthetic tornadoes and affiliated impact tallies generated by WUR may not be “realistic high-end cases” as suggested by Brooks et al. (2008) (Tables 2 and 3, Figure 3). The WUR “observation-constrained model” synthetics were generated using: 1) observed Doppler on Wheels (DOW) wind speed and size attributes at the time of maximum DOW-observed intensity for the 3 May 1999 Mulhall and Bridgecreek/Moore tornado events and 2) hypothetical cases that were representative of the worst of the tornado size/magnitude characteristics



**Figure 3.** Tornado and damage-intensity widths for the observed and synthetically derived events in Table 2. The segments for observed tornadoes represented were selected by subjectively determining where the tornado was at its widest during its most intense (as inferred by F/EF-scale) phase. Numbers correspond to: (1) WUR Mulhall, OK (MH), (2) WUR Bridgecreek/Moore (BC), (3) WUR Small (SM), (4) WUR Hybrid Reduced (HR), (5) WUR Hybrid (HB), (6) ASH Synthetic 6 (S6), (7) ASH Synthetic 5 (S5), (8) ASH Synthetic 4 (S4), (9) ASH Synthetic 3 (S3), (10) ASH Synthetic 2 (S2), (11) ASH Synthetic 1 (S1), (12) Plainfield, IL, (13) Joplin, MO (NWS), (14) Washington-Goldsby, OK, (15) El Reno, OK (2011), (16) Chickasha-Blanchard-Newcastle, OK, (17) Mulhall, OK, (18) Bridgecreek/Moore, OK (1999), (19) Newcastle-Moore, OK (2013), (20) El Reno, OK EF3 (2013), (21) 22 May 2004 Hallam, NE F4, (22) 4 May 2007 Hopewell, KS EF3, (23) 7 June 2008 Pardeeville-Cambria, WI EF3, (24) mean significant (F/EF2+) events from 1995-2011 (Table 3), and (25) mean violent (F/EF4+) from 1995-2011.

from the remotely sensed, DOW-derived attributes of these events (Table 2). Specifically, the path widths of three of the five synthetics used by WUR—i.e., the 6.6 km wide Hybrid Reduced (HR), 7.1 km wide Mulhall (MH), or 8.8 km wide Hybrid (HB)—are between 50-100% wider than the widest tornadoes ever recorded, the 2004 Hallam F4 and the 2013 El Reno EF3. The EF0+ path widths of the WUR tornadoes could be considerably wider than the reported values in WUR's Table 1 since the diameters stated in their study only included winds greater than  $43 \text{ m s}^{-1}$ , which is equivalent to the mid-range of an F/EF1 (the F1 range includes estimated three second gusts of  $35\text{-}52 \text{ m s}^{-1}$ , whereas the EF1 spans  $38\text{-}49 \text{ m s}^{-1}$ ). In the most extreme synthetic, the area swept out by  $\geq 43 \text{ m s}^{-1}$ , or EF1, winds is over  $500 \text{ km}^2$ , or almost the entire size of the City of Chicago ( $588 \text{ km}^2$ ). While there is historical precedent for extreme long-track events with over 30 events surpassing reported lengths of over 200 km since 1950, there is considerable discrepancy in the extreme width attributes found in the reported tornado record and WUR synthetics.

We evaluated the tornado width characteristics found in Table 2 and illustrated in Figure 3 by transposing each scenario onto a high-density, single-family housing area that typifies the developed landscape outside the Chicago central business district (CBD). Specifically, each of the path segments was constrained by a 10-km length, whereas the width was determined by the maximum F/EF0 or F/EF1 width attribute in Table 2. The 10-km length approximates the worst portion of the 2011 Joplin EF5 tornado segment that directly affected the developed area of the city (Figure 1.b and Figure 2). Thereafter, we centered each tornado segment over the intersection of Diversey and Laramie Avenues in Chicago's northwest side, calculating the area, 2010 population, and number of 2010 housing units and households affected in each scenario. The results highlight the dichotomy between WUR tornado scenarios and observed cases or scenario events based on the 2011 Joplin EF5 (Table 5). For example, the WUR HR, MH, and HB scenarios affect nearly 3.5 to 4.5 times the area of the "worst of" observed 2011 Joplin segments, even when length is restricted. The increase in area affected in these WUR scenarios leads to subsequent amplification of population (2.1-2.7 times the number of people compared to Joplin scenario), housing units (2.8-3.7 times), and households (2.8-3.6 times) impacted. The 31 May 2013 El Reno tornado was over three times the size of the Joplin event, suggesting that this recent case may provide the most realistic high-end width attribute to be employed in scenario work. In comparison, WUR HB, MH, and HR scenarios all affect areas 1.3 to 1.8 times larger than this modern width record holder. While it is possible that the widths found in WUR study could occur, they appear improbable based on even the most extreme cases found in the historical tornado record. The probability of WUR's high-end widths occurring over a high-density developed landscape such as that found in the Chicago region appears even more remote since

only 2.2% of the conterminous U.S. was characterized as urban and/or suburban ( $<0.69 \text{ ha}$  per housing unit) in 2000, rising to a forecasted 3.1% by 2020 (Theobald 2005).

#### *b. Macroscale changes in Chicago exposure*

To understand how tornado disaster potential has evolved, it is necessary to appreciate the character and trends of land-use dynamics through time and how those development patterns contribute to changes in exposure. Chicago has experienced a dramatic growth with a shift of population from the old industrial suburbs to the regions' new economy suburbs (Greene and Pick 2012, 2013). This pattern of expansion has led to decentralization of people and a metropolitan region with a polycentric quality – i.e., it has multiple downtowns, with many of those "new" downtowns in edge cities (Greene and Pick 2012). This development pattern is dominated by sprawl, which leads to an "expanding bull's-eye effect". This effect argues that targets—i.e., humans and their possessions—of geophysical hazards are enlarging as populations grow and spread. Consequently, it is not solely the population magnitude that is important in creating disaster potential, it is how the population, and its affiliated built environment, is distributed across space that determines how the underlying disaster components of risk and vulnerability are realized.

The total population for our study area has increased from just over 7.2 million in 1970 to 8.8 million 2010, a 21% surge. Most of the population gain was witnessed in the latter two decades, signifying population growth acceleration (Table 1). The number of housing units during the 1970-2010 period swelled from 2.4 million to just over 3.5 million, an increase of nearly 47.4%. Thus, the built environment (as measured by housing units) has increased at a faster rate than the number of people. As a consequence, any amplification in tornado losses from potential tornado disasters would be greater for insured or uninsured housing damages than human casualties.

To examine the development exposure change across our study area, we employed Theobald's (2005) land use classification on the grids and, thereafter, examined the changes temporally. Urban was defined as a grid cell that contained housing densities less than 0.1 ha per unit, suburban as 0.1–0.68 ha per unit, exurban as 0.68–16.18 ha per unit, and rural as greater than 16.18 ha per unit. For the region examined in this study (Figure 1.c), the number of urban classified cells increased from 4.5% to 5% from 1990-2010, whereas the number of rural cells decreased from 58.4% to 53.1% during the same period (Table 6). The rural-urban interface, which is characterized by suburban and exurban sprawl, witnessed a dichotomy in change by classification type. The percentage area that was categorized as suburban increased from 13.2% to 18% over the 20-yr period, resulting in the largest change (4.8%) in development type for the region. Conversely, the exurban classification changed relatively little during

the same time period. These data suggest that far more land was converted to a relatively high-density sprawl mode in comparison to the low-density development that typifies exurban. Collectively, the potential number of hazard “targets” has grown in magnitude and expanded, confirming the expanding bull’s-eye effect and increasing potential for disaster, at least on the scale of the metropolitan region.

### *c. Spatiotemporal assessment of exposure impacts for worst case scenarios*

To evaluate change in exposure to potentially catastrophic tornadoes, we employ two scenario-based approaches. The first uses a full-dimension synthetic tornado and, the second, a 10-km synthetic tornado segment. In both scenario procedures, we overlay the tracks/segments atop the block-level, AW-gridded exposure data to estimate the residents and numbers of housing units exposed to each hypothetical tornado case.

#### 1) FULL-DIMENSION SYNTHETIC SCENARIOS

Initially, we superimpose five full-length tornado paths based on synthetic S2 across the study area, with the paths spaced north-to-south, 15-20 km apart, and ceasing at the Lake Michigan shoreline. The use of a synthetic path removes the methodological concern expressed by Wurman and Alexander (2005), WUR, and Wurman et al. (2008a) that transposing historical events that tracked over largely rural locations (in the case of many of the tornadoes in the 3 May 1999 outbreak or the Plainfield event 28 August 1990) atop urban conglomerations (Dallas-Fort Worth in Rae and Stefkovich (2000) and Chicago suburbs in Hall and Ashley (2008)) leads to underestimation of tornado disaster potential in more dense residential areas. Wurman and Alexander (2005) and Wurman et al. (2008a) argue that there can be notable differences between the EF-scale quantified damage caused by strong-to-violent winds on the observable developed landscape and the likely extent of strong-to-violent modeled surface winds based on observations from DOWs due to the lack damage indicators in rural locations. This discrepancy surfaced in the contentious rating of the 31 May 2013 El Reno tornado. The lack of damage indicator restriction can minimize damage potential of tornadoes when historical events, and their damage-intensity patterns, are transposed to a location with dramatically different development character. Based on prior assessments, the S2 path comprises plausible “worst-case” dimensions and magnitude attributes since it is constructed from contemporary violent tornado footprints and damage spatial characteristics from the worst segment of the Joplin EF5 path. The scenario paths were oriented from west-southwest to east-northeast, which is the dominant tornado direction mode found in a prior climatology (Suckling and Ashley 2006).

Four of the five scenarios experienced greater than double-digit percentage increases in population and housing units from 1990-2010 (Table 7). The only

scenario that had a decrease in an exposure metric was scenario P5. This case traversed the urban south side of Chicago, a region that has witnessed a notable loss in population during this period (Greene and Pick 2012). Despite the population loss, the hypothetical tornado path affected 7.3% more housing units. This dichotomy in exposure is due to the population decrease found in the aforementioned urban region, a lack of corresponding housing unit decrease in that same area, and increases in suburbanization and exurbanization across the first half of the track. Scenario P1 had the largest increase in population (housing unit) change, with 49% (57%) increase in exposure metrics. The P1 scenario impacted the north side of Chicago; an area that has undergone some of the greatest population and housing unit increases in the region (Table 1), with most of that development falling into suburban and exurban land use types (Figure 2.c-d). Scenario P4 moved through locations consisting largely of suburban and urban development, terminating near the Chicago CBD. The population increase along this path was bimodal – with no notable increase along the middle of the track, bounded by large increase in both population (Figure 2.b) and housing units (not shown) due to suburban development near the first third of the track and urban-core, high-rise residential development near the tornado’s terminus. The latter, CBD-focused increase in population and housing units is a recent reversal in long-term development trends found in many cities (Census Bureau 2012b). While suburbanization and exurbanization has continued in the past decade, a secondary, focused “inward migration” has taken place as more jobs in and near the CBD attract more residents desiring to move downtown that, in turn, becomes a magnet for more employers (Ehrenhalt 2013, Hinz 2013). From 2001-2010, Chicago underwent the largest numeric and percentage gain in its downtown area of any of the largest cities in the U.S. (Census Bureau 2012b, Hinz 2013). This demographic transformation illustrates how the continually evolving spatiotemporal character of development can dramatically influence the disaster potential landscape, especially at the microscale.

Scenarios P2 and P3 tracked across locales that have witnessed growth, but not of the magnitude found along the city’s more focused ring of development located approximately 60-80 km from the CBD (Greene and Pick 2013). Nevertheless, the development found near the origin of these paths still leads to 15-22% increases in exposure metrics during this two-decade period for the scenarios.

#### 2) 10-KM SYNTHETIC SCENARIOS

Using a synthetic’s entire path length—e.g., 45-67 km (Table 2)—leads to scenarios where the damage footprint inevitably stretches across multiple development types, causing difficulty in evaluating specific land-use change effects on disaster potential. To generate a more focused analysis of how development has influenced disaster potential, we use a 10-km segment of the synthetic S2 (Figure 2.c) to target

specific land use types and their changes from 1990 to 2010. As discussed prior, the 10-km segment we use is representative of a tornado striking a developed region.

First, we placed the 10-km S2 segment across particular development types to assess changes in exposure where the land use has been relatively constant over the 20-yr period as determined by an evaluation of land-use data derived from the three decennial censuses (e.g., Figure 2.c). This promotes an evaluation of how each of the differing land use types is contributing to the overall change in tornado exposure (Table 8).

Both urban tornado scenarios, Ur1 and Ur2, experienced losses in population, reconfirming the slow exodus of people from the immediate area surrounding the CBD. The near-central city of Chicago, as with most large cities Midwest and Northeast, has been defined by perennial population declines (excluding a small expansion in the 1990s) since the 1950s (Greene and Pick 2012). These declines are due to the abandonment of the area immediately around the urban core by the middle class, giving rise to an urban underclass characterized by little upward mobility that results in poor neighborhoods, high crime rates, and diminished amenities (Wilson 1986, 1987; Hudson 2006; Greene and Pick 2012). Whereas the exposure in these areas may be stable or have decreased during the period examined, other components of vulnerability may have changed that could result in far greater disaster potential. Conceptually, vulnerability can be differentiated by three constituents: exposure (characteristics of the natural and/or built environment that position a system to be affected by a hazard; in this study, people and their housing units), sensitivity/susceptibility (degree to which a system is affected by hazard conditions), and adaptive capacity (ability for the system to cope or adapt to hazard conditions) (Adger 2006, Polksy et al. 2007, Fekete 2012, Morss et al. 2011). We have employed a disintegrative methodology that examines a distinct component of vulnerability (exposure), which we argue promotes a more measured and quantified analysis of that element. However, this singular analysis does not permit the discovery of how important the other constituents of vulnerability are, and how they integrate with one another, in these particular cases. For instance, in areas that have witnessed urban decay, people would arguably have increased susceptibility and decreased adaptive capacity to disasters that could lead to far greater disaster consequences (Wisner et al. 2004; Paul 2011).

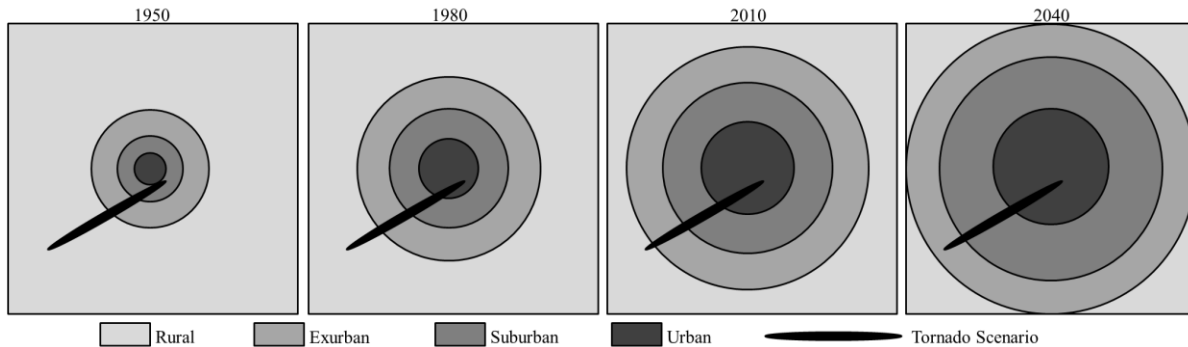
Scenario segments in the suburban locations, Su1 and Su2, generated mixed results. Changes in affected population in the segments were negligible, with both areas experiencing increases in housing units. These areas of DuPage (Su1) and Cook (Su2) Counties were developed largely prior to the period of analysis (Figure 2.d), with only limited, fill-in development increasing the housing unit metric. Of the segment scenarios placed over temporally consistent land-use types, exurban

scenario Ex1 underwent the greatest amplification in exposure magnitude. The area of central Kane County has continued to see development, with much of the area already, or on the cusp of, converting from exurban to suburban classification. Therefore, even in low-density developed areas, there has been a continued escalation in density and, thus, exposure. Uniquely, scenario Ex2 witnessed a notable drop in population exposure, with a near 20% increase in housing units, with much of that increase occurring during the 1990-2000 period. Both exposure measurements for the two rural cases examined, Ru1 and Ru2, decreased. Though rural population loss is endemic to many rural areas in the United States (McGranahan and Beale 2002), the decreases found here must be deciphered with caution. The decreases in population are on the order of a couple dozen, with housing unit losses sometime less than 1 unit per scenario. In comparison to the exposure values found for urban, suburban, and even exurban, these impacted numbers are very small.

Next, five track segments were placed explicitly across locations where kernel density estimation analyses (not shown) on land-use change data (e.g., Figure 2.d) revealed clusters of grid cells that underwent rural-to-exurban or exurban-to-suburban change (Table 8). This analysis targets how low- and high-density sprawl has contributed to the overall disaster potential picture. Track segments T1 and T2, are represented by areas that transitioned from rural to exurban land use classifications. Both T1 and T2 track segments illustrate positive percentage changes in population and housing units impacted from 1990 to 2010, though results are tempered by the low affected counts. The amplification in tornado exposure for the T1 and T2 segments is due to increased development and affiliated sprawl apparent in these areas over the past two decades. Areas that were once largely row-crop farmland have since transitioned to exurban development, incrementally increasing hazard targets and the expanding bull's-eye effect. Tornado scenario segments T3, T4, and T5 are characterized by areas that have transitioned from exurban to suburban land use classifications. All three of these tornado scenario segments exemplify extremely large (>150%) positive percent increases in population and housing units impacted from 1990 to 2010. Indeed, these segments contain collectively the largest percentage increases found in any of the segment scenarios suggesting that it is this particular development change that has led to the greatest expansion in the exposure to weather hazards in this region.

#### 4. CONCLUSION

We have employed the contextual argument that exposure is a "condition sine qua non for disaster risk to exist" (UNDP 2004). Moreover, population growth is not spatially uniform and, therefore, exposure is not distributed evenly across the landscape. For instance, cities and suburbs grow directionally and, consequently, the evaluation of the spatial character of exposure is as



**Figure 4.** A conceptual model of the “expanding bull’s eye effect” for a hypothetical metropolitan region that is characterized by increasing development spreading from an urban core over time. A sample tornado scenario is overlaid to show how expanding development creates larger areas of potential impacts from hazards.

important as other interrogatives. Due to data, computational, and methodological restrictions, research quantifying changes in hazard exposure has been relatively limited. Using conventional spatiotemporal change methods on standard, relatively large, enumeration units, previous works (e.g., Hall and Ashley 2008, Paulikas and Ashley 2011) have investigated shifts in weather-related exposure at the metropolitan scale. These methods lacked the sophistication necessary to assess a spectrum of geographic extents and generate more substantial conclusions regarding exposure’s culpability in augmenting tornado disaster consequences. Preceding evaluations of exposure tend to aggregate at spatial extents far larger than the hazard footprint, especially for microscale hazards spawned by severe thunderstorms. The incongruence of spatial scales of analysis often precluded an assessment of the relationship between the underlying constituents requisite for disaster. This investigation offered an initial step toward rectifying these perceived deficiencies, fostering a homogenized approach for assessing and quantifying changes in fine-scale weather hazard exposure and providing a framework for future work exploring exposure and vulnerability’s contribution to disasters.

Specifically, through a geographic lens, we assessed how an increasing and spreading population is leading to substantial growth in tornado hazard exposure rates, appearing to offset, or counteract, contemporary scientific and technological advances in mitigation (e.g., warning systems, Doppler radar, etc.) as exemplified in recent tornado disasters. We employed spatial data modeling and spatial analytic approaches that appraised contemporary changes in the relationship between tornadoes and the distribution of people and their residences for the case of Chicago. Results proved that, generally, the number of people and their housing continues to grow and geographically expand, promoting an increasing hazard target, or what we termed the expanding bull’s eye effect. Metropolitan-scale assessments of Chicago’s demographic, housing unit, and land-use types confirm that, simply, more

people and their possessions are in the potential path of tornadoes. This finding is not entirely unexpected, but we illustrate specifically how differing development types lead to varying exposure rates that contribute to the unevenness of potential weather-related disasters across the landscape. For instance, suburbanization development character associated with high-density sprawl has led to the greatest change in exposure landscape in the Chicago area. Conversely, along the periphery of the urban core, long-term population loss has led to decreasing amounts of people to be affected; yet, those that remain may be highly vulnerable due to enhanced sensitivity/susceptibility and reduced adaptive capacity (e.g., see Klinenberg (2002)) – components of vulnerability we did not examine in this study. More recently, inward migration to CBDs (Census Bureau 2012b, Ehrenhalt 2013) has promoted a very dense exposure in the urban core with concentrated catastrophic disaster potential that could potentially overwhelm the critical infrastructure sectors (Homeland Security 2009) of most, if not all, cities, including Chicago.

A simple conceptual model (Figure 4) is provided to illustrate how spatiotemporal development changes found in metropolitan regions have led to and will continue to foster an expanding bull’s eye effect, placing ever increasing amounts of “targets”—people, built environments, and infrastructure—in harm’s way of tornadoes and other geophysical and technical hazards. We have argued it is not solely the population magnitude that is important in creating disaster potential, it is how the population, and its affiliated built environment, is distributed across the geographical landscape that defines how the fundamental components of risk and vulnerability are realized in a disaster. The model proposed reveals the broad concept of the expanding bull’s eye effect with the inferred understanding that each city and/or regional development footprint will be constrained by a diverse set of social, economic (Hardaway 2011), political (e.g., land-use planning, park designation, etc.), and physical (e.g., Lake Michigan in Chicago’s case) elements.

In addition, our research appraised the viability of using a gridded framework for assessing the changes in census-derived exposure data. The gridded methodology removes the spatial unit variation problem found when using two or more census time stamps (Cai et al. 2006) and promotes an evaluation of temporal changes in the underlying vulnerability, a dimension often excluded from exposure studies.

The investigation also assessed tornado dimensions employed in previous scenario-based research. An analysis of historical significant and violent tornado events found that the high-end width scenarios in WUR are not likely representative of even the most extreme potential tornadoes. We offer a structure for synthetic development based on observed damage indicators for a modern catastrophic event (2011 Joplin EF5). This methodology promoted a flexible, yet observationally constrained framework for developing tornado synthetics that can be used in models to assess potential social, physical, and economic losses from tornadoes. Additional work conflating damage indicators, mobile Doppler radar data, and in situ observations is required to build a more robust and realistic tornado scenario model.

While climate change may amplify the risk of certain hazards, the root cause of escalating disasters is not necessarily event frequency, or risk, related. Rather, as affirmed by previous research (e.g., Changnon et al. 2000, Cutter 2010, Bouwer 2011, Barthel and Neumayer 2012, Simmons et al. 2013) and illustrated herein, the growing trend in disasters is likely due to 1) increasing density and spread of humans and property in harm's way, or exposure, and 2) increasing vulnerability of the population. We have focused explicitly on the physical exposure components of population and their residences to tornadoes in the third largest metropolitan area in the U.S. – a region that has a relatively elevated risk of tornado risk (Brooks et al. 2003). This research methodology could be replicated across a variety of spatiotemporal domains, as well as for other hazards. Recent tornado catastrophes (e.g., 27-28 April 2011 tornado outbreak, 22 May 2011 Joplin tornado, 20 May 2013 Moore, etc.) reveal that there is much to be learned about how hazards interact with society and, perhaps more importantly, how society interacts with hazards. Studies engaging a worst-case hazard scenario approach using representative hazard models on high spatial resolution datasets of historical or forecast vulnerability constituents could spur mitigation activities and policy changes with the goal of reducing hazard impacts. An essential part of that research must focus on understanding how the exposure landscape has transformed over time and how those spatiotemporal changes may influence the tasks of warning, rescue, and recovery should a catastrophic scenarios come to fruition. Discovered spatiotemporal trends of hazard exposure will assist policy makers, hazard scientists, and the public by illustrating the role amplifying exposure has on the increasing hazard impacts.

## 5. REFERENCES

Available upon request. Please contact first author.



**Table 1.** Mean tract (1960-2010) and block (1990-2010) size area (km<sup>2</sup>) by individual county and all counties (total), as well as the percentage change in population (Pop.) and housing units (HU) from 1970 to 2010 and 1990 to 2010.

Year	Boone	Cook	DeKalb	DuPage	Grundy	Kane	Kendall	Lake	LaSalle	McHenry	Will	Total
<b>1960 Tract</b>	-	2.21	-	16.14	-	45.25	-	34.76	-	197.85	70.96	7.59
<b>1970 Tract</b>	121.70	2.11	-	13.21	-	30.16	-	20.98	-	113.06	55.00	7.44
<b>1980 Tract</b>	121.70	2.02	-	9.47	-	25.14	119.39	16.44	-	93.11	46.81	7.39
<b>1990 Tract</b>	121.70	1.84	78.31	7.51	123.86	19.96	104.46	12.54	110.13	60.88	27.85	9.40
<b>2000 Tract</b>	121.70	1.85	78.31	5.93	123.86	20.26	104.46	8.06	110.13	33.68	26.83	8.91
<b>2010 Tract</b>	104.34	1.88	78.27	4.03	111.47	16.56	83.48	7.95	106.17	30.42	14.47	8.30
<b>1990 Block</b>	0.6988	0.0474	0.6384	0.0798	0.5873	0.2162	0.5952	0.1333	0.5595	0.3456	0.2777	0.1646
<b>2000 Block</b>	0.5291	0.0387	0.5188	0.0541	0.4797	0.1597	0.4403	0.0950	0.4999	0.2221	0.1938	0.1262
<b>2010 Block</b>	0.4124	0.0251	0.4137	0.0501	0.2280	0.1273	0.2154	0.0762	0.4446	0.1965	0.1515	0.0910
<b>1970-2010 Pop. % Change</b>	112.9%	-5.4%	46.8%	87.9%	88.7%	105.3%	335.0%	83.8%	2.3%	176.8%	173.4%	21.0%
<b>1970-2010 HU % Change</b>	75.8%	1.8%	34.9%	17.3%	54.8%	62.3%	191.1%	36.2%	6.6%	68.5%	89.6%	16.0%
<b>1990-2010 Pop. % Change</b>	144.7%	17.5%	102.7%	152.4%	126.4%	136.2%	418.7%	135.7%	32.7%	219.8%	223.9%	47.4%
<b>1990-2010 HU % Change</b>	74.0%	7.8%	50.2%	21.8%	58.0%	63.3%	193.3%	42.0%	14.0%	75.9%	93.3%	20.5%

**Table 2.** Tornado parameters and attributes from 1) violent events from 1990, 1999, 2011, and 2013, 2) WUR synthetics, and 3) our synthetics, which are based on mean length (km) and width (m) information gathered from all U.S. violent tornadoes from 1995 to 2011 that contained information on those elements. Area (km<sup>2</sup>) swept out by each tornado's reported (Enhanced) Fujita Scale class is provided.

Path	Date	Min-Max F/EF Scale	Fatalities	Path length	Max width	F/EF0 area	F/EF1 area	F/EF2 area	F/EF3 area	F/EF4 area	F/EF5 area	Total area
<b>Tornado event</b>												
(1) Plainfield, IL	8/28/1990	F1-F5	29	26.4	548	-	8.57	2.57	0.44	0.12	0.02	11.72
(2) Bridgecreek-Moore, OK	5/3/1999	F1-F5	36	61	1609	-	18.11	12.31	12.70	5.51	0.87	49.50
(3) Mulhall, OK	5/3/1999	F1-F4	2	63	1609	-	31.00	17.36	6.41	12.64	-	67.41
(4) Joplin, MO (NWS)	5/22/2011	EF1-EF5	158	35	1463	-	28.71	9.58	3.85	2.22	1.34	45.70
(5) El Reno, OK	5/24/2011	EF0-EF5	9	101	1609	24.65	32.63	21.83	17.06	2.55	0.42	99.14
(6) Washington-Goldsby, OK	5/24/2011	EF0-EF4	0	37	805	3.58	3.43	3.16	2.21	0.70	-	13.08
(7) Chickasha-Newcastle, OK	5/24/2011	EF0-EF4	1	53	805	8.06	10.17	5.12	2.68	1.12	-	27.15
(8) Newcastle-Moore, OK	5/20/2013	EF0-EF5	23	27	1737	11.88	5.45	2.57	1.90	1.38	0.12	23.30
(9) El Reno, OK	5/30/2013	EF0-EF3	9	26	4184	-	-	-	-	-	-	73.06
<b>Wurman et al. (WUR) synthetics</b>												
(10) Mulhall, OK (MH)	5/3/1999	F1-F4	-	60	7050	-	225.33	91.05	99.79	45.87	-	462.03
(11) Bridgecreek/Moore, OK (BC)	5/3/1999	F1-F5	-	60	2315	-	65.02	27.44	20.09	11.28	19.28	143.11
(12) Hybrid (HB)	-	F1-F5	-	60	8800	-	235.19	105.40	73.59	36.88	72.70	523.76
(13) Hybrid Reduced (HR)	-	F1-F4	-	60	6580	-	174.85	73.47	75.32	61.80	-	385.45
(14) Small (SM)	-	F1-F3	-	60	548	-	13.07	9.97	7.34	-	-	30.38
<b>Ashley et al. (ASH) synthetics</b>												
(15) Synthetic 1 (S1)	-	EF0-EF5	-	45.21	873	20.63	4.36	4.22	5.06	4.37	1.44	40.09
(16) Synthetic 2 (S2)	-	EF0-EF5	-	67.3	1390	49.72	9.57	9.99	12.00	10.37	3.41	95.06
(17) Synthetic 3 (S3)	-	EF1-EF5	-	45.21	873	-	9.04	8.71	10.42	8.97	2.95	40.09
(18) Synthetic 4 (S4)	-	EF1-EF5	-	67.3	1390	-	21.46	20.66	24.71	21.25	6.98	95.06
(19) Synthetic 5 (S5)	-	EF1-EF5	-	45.21	873	-	14.75	8.97	8.33	5.01	3.03	40.09
(20) Synthetic 6 (S6)	-	EF1-EF5	-	67.3	1390	-	34.99	21.26	19.75	11.87	7.18	95.06

**Table 3.** Mean length (km) and width (m) attributes by damage class for 1995-2011 U.S. tornadoes.

F/EF Damage	Count	Mean Length	Mean Width
F/EF0	13232	1.90	45.43
F/EF1	5830	6.28	127.41
F/EF2	1747	13.18	286.88
F/EF3	506	26.84	568.84
F/EF4	115	42.72	815.07
F/EF5	13	67.30	1389.89
<b>Total (F/EF0+)</b>	<b>21443</b>	<b>4.85</b>	<b>104.68</b>
<b>Significant (F/EF2+)</b>	<b>2381</b>	<b>17.81</b>	<b>378.34</b>
<b>Violent (F/EF4+)</b>	<b>128</b>	<b>45.21</b>	<b>873.45</b>

**Table 4.** The area (km<sup>2</sup>) and proportion of each EF damage class for the 10-km segment of the Joplin tornado that impacted developed areas.

Damage	Marshall et al. (2012) EF0-EF5		Marshall et al. (2012) EF1-EF5		NWS (2011) EF1-EF5	
	Area	% area of track segment	Area	% area of track segment	Area	% area of track segment
EF0	7.949	51.1	-	-	-	-
EF1	1.695	10.9	1.695	22.3	6.368	36.44
EF2	1.645	10.57	1.645	21.62	3.904	22.35
EF3	1.982	12.74	1.982	26.05	3.652	20.91
EF4	1.719	11.05	1.719	22.58	2.206	12.63
EF5	0.567	3.64	0.567	7.45	1.339	7.67
<b>Total</b>	<b>15.557</b>	<b>100</b>	<b>7.608</b>	<b>100</b>	<b>17.469</b>	<b>100</b>

**Table 5.** Tornado segment impact characteristics based on a fixed 10-km length and corresponding width attributes found in Table 2, ranked from highest to lowest area impacted. The segments were centered over Diversey and Laramie Avenues on Chicago's northwest side.

Tornado	Area (km <sup>2</sup> )	Population Affected	Housing Units Affected	Households Affected
WUR HB	78.13	497,226	184,921	167,168
WUR MH	70.90	456,016	168,697	152,616
WUR HR	58.92	388,177	141,853	128,627
El Reno, OK (2013)	41.58	292,241	104,088	94,230
WUR BC	23.27	184,388	65,739	59,898
Joplin, MO (NWS)	17.47	137,763	50,428	45,974
Mulhall, OK	14.29	114,679	41,270	37,743
ASH S4	13.96	111,684	40,175	36,736
ASH S2	13.96	111,734	40,185	36,746
ASH S6	13.96	111,596	40,157	36,718
Newcastle-Moore (2013)	13.70	108,692	38,513	35,204
Bridgecreek-Moore, OK	13.54	110,263	39,660	36,176
El Reno, OK (2011)	11.81	88,952	32,815	29,921
ASH S3	8.77	69,044	25,209	23,114
ASH S1	8.77	69,191	25,219	23,122
ASH S5	8.77	69,123	25,214	23,119
Chickasha, OK	8.57	70,130	24,763	22,457
WUR SM	4.97	38,368	14,124	12,976
Washington-Goldsby, OK	4.91	39,216	13,971	12,847
Plainfield, IL	4.50	34,161	12,208	11,217

**Table 6.** Number of 0.16 km<sup>2</sup> cells, and percentage of total area, for each land use type in the 11-county Chicago region for 1990, 2000, and 2010.

Land-use Type	Count			% of Total Area sq. km			% Change
	1990	2000	2010	1990	2000	2010	1990-2010
Urban	4,759	5,129	5,343	4.5	4.8	5.0	0.6
Suburban	14,052	16,430	19,186	13.2	15.4	18.0	4.8
Exurban	25,707	25,619	25,543	24.0	23.9	23.9	-0.2
Rural	62,622	59,962	57,068	58.4	55.9	53.1	-5.2

**Table 7.** Number of people and housing units affected and affiliated 1990-2010 percent changes of total impacted for five simulated tracks of tornadoes across Chicago region based on the S2 scenario (cf. Figure 2.c).

Position	Year	Population				Housing Units			
		EF2-EF5	EF4-EF5	EF0-EF5	1990-2010 % Change	EF2-EF5	EF4-EF5	EF0-EF5	1990-2010 % Change
1	1990	14,155	5,451	35,947		5,554	2,138	13,921	
	2000	19,953	7,612	52,418		7,167	2,715	18,906	
	2010	22,292	8,591	56,327	56.7%	8,206	3,160	20,741	49.0%
2	1990	24,790	9,600	63,458		9,731	3,764	24,393	
	2000	25,780	9,786	69,923		10,022	3,802	26,765	
	2010	28,269	10,916	74,920	18.1%	11,355	4,396	29,646	21.5%
3	1990	38,935	14,867	104,961		14,975	5,700	40,335	
	2000	43,592	16,743	115,892		16,734	6,450	43,853	
	2010	46,300	17,841	120,828	15.1%	18,013	6,938	46,744	15.9%
4	1990	57,214	21,772	161,378		22,881	8,505	65,782	
	2000	66,676	25,130	185,859		25,779	9,477	75,043	
	2010	73,022	27,292	205,771	27.5%	32,009	11,599	95,139	44.6%
5	1990	37,411	14,240	102,587		12,857	4,932	34,798	
	2000	39,278	15,090	105,294		14,048	5,399	37,413	
	2010	35,461	13,624	95,105	-7.3%	13,999	5,373	37,334	7.3%

**Table 8.** Number of people and housing units affected and affiliated 1990-2010 percent changes of total impacted for simulated 10-km tornado segments across Chicago region based on the S2 scenario (cf. Figure 2.c-d). Counts for those areas affected by significant (EF2+) and violent (EF4+) damage are also provided.

Position	Year	Population				Housing Units			
		EF2-EF5	EF4-EF5	EF0-EF5	1990-2010 % Change	EF2-EF5	EF4-EF5	EF0-EF5	1990-2010 % Change
Ur1	1990	48,104	18,424	115,971		19,500	7,089	49,575	
	2000	47,643	18,487	115,881		21,245	7,961	53,473	
	2010	44,705	17,392	111,419	-3.9%	23,491	9,017	60,171	21.4%
Ur2	1990	35,505	13,527	91,753		13,895	5,302	35,497	
	2000	33,908	12,939	87,094		13,211	5,021	33,744	
	2010	27,001	10,299	70,006	-23.7%	12,983	4,963	32,927	-7.2%
Su1	1990	8,471	3,238	22,288		3,152	1,209	7,848	
	2000	8,154	3,010	22,556		3,031	1,149	7,812	
	2010	8,288	3,097	22,388	0.4%	3,201	1,216	8,066	2.8%
Su2	1990	5,999	2,270	16,568		1,896	715	5,357	
	2000	5,960	2,231	17,120		1,979	744	5,868	
	2010	5,951	2,303	16,155	-2.5%	2,180	841	6,138	14.6%
Ex1	1990	958	375	2,365		283	111	704	
	2000	1,267	486	3,306		379	145	989	
	2010	1,360	519	3,595	52.0%	447	171	1,181	67.7%
Ex2	1990	124	47	366		39	15	114	
	2000	126	48	385		46	18	139	
	2010	112	43	341	-6.8%	46	18	136	19.7%
Ru1	1990	26	10	68		9	3	23	
	2000	24	9	64		9	3	23	
	2010	19	7	51	-24.6%	9	3	23	-1.6%
Ru2	1990	23	9	65		8	3	22	
	2000	18	7	49		7	3	18	
	2010	15	6	41	-36.8%	7	3	19	-15.7%
T1	1990	61	24	173		20	8	57	
	2000	111	43	329		37	14	108	
	2010	241	93	626	261.2%	82	32	211	271.6%
T2	1990	62	23	175		22	8	61	
	2000	91	39	211		32	13	75	
	2010	69	26	188	7.3%	26	10	73	19.9%
T3	1990	1,540	591	4,367		578	221	1,628	
	2000	8,008	3,067	21,058		2,585	986	6,912	
	2010	9,374	3,638	23,900	447.3%	3,098	1,200	8,108	398.0%
T4	1990	3,163	1,325	7,045		1,061	443	2,363	
	2000	6,724	2,703	14,620		2,137	865	4,730	
	2010	8,624	3,424	19,814	181.2%	2,805	1,119	6,596	179.1%
T5	1990	388	123	2,377		150	48	863	
	2000	2,603	960	8,576		879	325	2,816	
	2010	4,888	1,917	13,394	463.5%	1,700	667	4,518	423.6%