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Thunderstorm Hazard vulnerability for the Atlanta, Georgia metropolitan region

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Abstract Most U.S. metropolitan regions have experienced urban "sprawl," or the outward spreading of urban development from city centers. For cities lying in areas prone to severe weather, the sprawl phenomenon exposes greater numbers of developed areas and inhabitants to a variety of thunderstorm hazards. This study's principal goal is to determine how urbanization growth patterns affect a region's vulnerability to severe weather events. To assess how sprawl may impact vulnerability to tornadoes, hail, and convective wind events, an analysis examining potential loss may be utilized. This study employs two distinct approaches to examine how the Atlanta area's rapid and extensive development during the latter half of the twentieth Century has affected its overall potential exposure to thunderstorm hazards. First, archived census data are used to estimate overall impacts from hypothetical significant tornado, nontornadic convective wind, and hail events occurring at different time periods throughout several locations in the Atlanta metropolitan region. Second, economic factors are integrated into the analysis, which assists in determining how these hypothetical severe event scenarios may have changed from a cost standpoint if they were to occur in 2006 as opposed to 1960.

Keywords Severe convective storms · Thunderstorms · Atlanta · Urbanization · Tornado · Hail · Wind

1 Introduction

The Atlanta Metropolitan Statistical Area (MSA) is one of many city regions that have grown rapidly since 1960 due to the urban sprawl phenomenon. The term sprawl denotes the outward spreading of a city into surrounding undeveloped regions (Gillham 2002),

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which is commonly characterized by zones of low-density housing and the usage of an automobile as the primary means of transportation (Squires 2002). As metropolitan regions spread out over larger areas of land, however, they also become expanded targets for potentially destructive weather (Changnon 2008; Hall and Ashley 2008). Today, the Atlanta MSA is arguably far more vulnerable to severe events than it has been in the past, as it comprises at least 13 counties with populations of at least 100,000, as opposed to only three counties with those population characteristics in 1960 (U.S. Census 2008, 2009). Additionally, the Atlanta region is located in an area where severe weather is not uncommon, as evidenced by a strong downtown tornado event in 2008 (Nelson and Rothfusz 2009) and massive flooding in 2009 (Shepherd et al. 2010).

To gauge the Atlanta MSA's change in potential exposure to severe weather events, this study undertakes two vulnerability assessments for the region. "Vulnerability" is defined in this investigation as lives, structures, and wealth that may be potentially exposed to an environmental hazard event (Smith 2001; Borden et al. 2007). Given this characterization, vulnerability may simply be regarded as potential loss (Cutter et al. 2003). Several previous studies (Davidson and Lambert 2001; Cutter et al. 2003; Rygel et al. 2006) have further defined vulnerability to include a series of socioeconomic factors that may enhance or reduce an individual's potential to hazard exposure. The primary focus of this study, however, is to assess broadly the sheer number of potential severe convective hazard targets that have likely changed due to the expansion of the Atlanta MSA. The two vulnerability appraisals in this study include: (1) hypothetical damage swaths of significant tornado, nontornadic convective wind, and hail events that are placed throughout the Atlanta MSA to illustrate how many persons and housing structures could have been impacted potentially from a severe event at different points in the historical timeline; and (2) a series of economic factors (inflation, wealth per capita, changes in housing unit structures) that are used to gauge how severe events in 2006 would affect damage estimate totals relative to 1960.

2 Background

The Atlanta MSA was once declared by *Time Magazine* in 1999 as the "fastest-spreading human settlement in history," with 500 farmland acres, on average, being set aside for development on a weekly basis (Gillham 2002). Historically, sprawl has been fueled by desires of purchasing larger quantities of land for less money and "escaping" perceived negative attributes of city life, such as traffic congestion and air pollution (Cavin 2003). These factors, coupled with a series of Southern U.S. job booms witnessed throughout the 1970s, 80s, and 90s, all played a large role in the Atlanta region nearly doubling in the number of counties comprising the metropolitan area in just over two decades (Cromartie 2001; Squires 2002; Katz et al. 2005; Metro Atlanta Chamber of Commerce 2005). Additionally, Atlanta is located in a relatively flat physiographic area and has not been inhibited from expansion by mountains or water accessibility issues as has often been seen with Western cities (Cavin 2003).

Since 1960, the U.S. urban population increased by more than 50% and developed regions surrounding urban centers have more than doubled (World Almanac 2008), resulting in larger metropolitan regions existing in areas prone to severe weather outbreaks than in years past. While weather forecasting improvements and awareness have led to a decrease in thunderstorm-related deaths over the past several decades, property damage costs and overall exposure to severe events have been increasing steadily throughout this time (Doswell et al. 1999; Changnon et al. 2000; Changnon 2008; Ashley and Gilson 2009). These property damage increases have coincided with a decrease in agricultural losses relative to the total damages incurred by various thunderstorm hazards (Changnon 1999; Changnon and Burroughs 2003).

Examples illustrating how sprawl can lead to a costly thunderstorm disaster include the 2001 Missouri hailstorm event, which produced \$1.9 billion in damages. It was the ninth costliest U.S. weather disaster at the time of the event and produced damage over parts of the Kansas City, Columbia, and St. Louis metropolitan regions that were largely open farm fields just two decades earlier (Changnon and Burroughs 2003). Similarly, Hall and Ashley (2008) revealed that if the 1990 F5 Plainfield, IL, tornado event had occurred 10 years later, the number of people impacted by the event would have increased by an estimated 76%, and the number of housing units impacted would have increased by an estimated 66%. The Plainfield tornado would have also likely been a costlier disaster, as the two Illinois counties directly affected by the event (Will and Kendall Counties) sustained respective median home value increases of 28.2 and 16% between 1990 and 2000 (Hall and Ashley 2008). Questions have arisen as to whether urban landscapes have affected severe weather probability through the urban heat island (UHI) effect, which has increased storm initiation over many U.S. cities (Huff and Changnon 1973; Bornstein and Leroy 1990; Dixon and Mote 2003; Bentley et al. 2010). Recent studies (Parker and Knievel 2005; Blumenfeld 2008) suggest, however, that the UHI effect cannot be clearly defined as a primary factor that consistently enhances or diminishes an urban region's likelihood to a severe weather event, and further investigations would need to be undertaken.

Thunderstorm hazard events classified as "severe" have historically featured hail measurements of at least 2 cm (3/4″) in diameter (updated to 1″ diameter measurements as of Jan. 2010), wind speeds measured at 26 ms^{-1} (50 kts), and/or tornadoes (Doswell 2001; NOAA 2010). These thresholds define points of intensity for thunderstorm hazards where the potential for widespread damage typically begins (Doswell 2001). Recent studies (Brooks et al. 2003; Doswell et al. 2005; Blumenfeld 2008) have also established "significant" severe thresholds to separate events that are questionable in creating damage from ones that have a substantially larger potential to do so. In these studies, "significant" severe events feature 33.5 ms^{-1} (65 kt) wind speeds, 5.1 cm (2″) diameter hail, and F2 + tornado intensities, which are regarded as intensities that will likely create widespread damage and disruption. All hazard events incorporated into this study will assume significantly severe intensities, as the investigation is prefaced on assessing exposure to "worst case scenario" types of thunderstorm events.

3 Methodology

This investigation employs two distinct potential loss assessment methodologies for the Atlanta MSA region, including: (1) temporal severe event exposure estimates to lives and property, and (2) a temporal cost factor change calculation. In these assessments, three separate areas of the 28 counties comprising the present-day Atlanta MSA are subdivided into three 'ring' county sections: an Urban Core (4,538 km^2 in area), an Inner Ring (8,472 km^2 in area), and an Outer Ring (9,022 km^2 in area; Fig. 1). The subdivision of these counties permits an examination of how the ring-like urbanization pattern has impacted thunderstorm hazard vulnerability throughout the Atlanta MSA.

The study uses U.S. Census data, which feature county population and housing unit values for every 10-year period from 1960 through 2000 and also for 2006 (U.S. Census

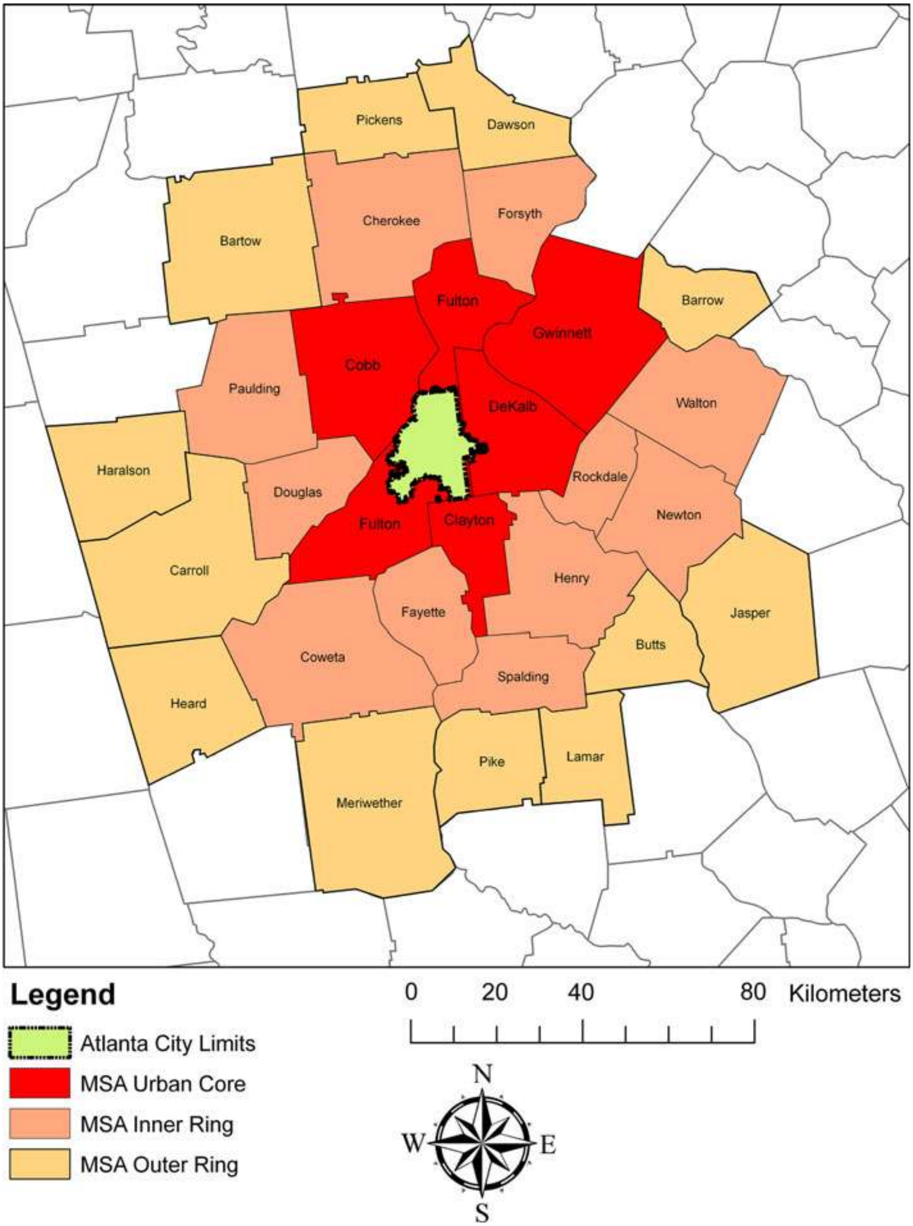

Fig. 1 The Urban Core, Inner Ring, and Outer Ring sections of the Atlanta MSA

Bureau 2008, 2009). Economic data are also utilized, which includes indices for inflation and wealth per capita (Bureau of Economic Analysis 2010a, b). All analyses in this project are conducted on the county level, which is the largest geographic scale available for downloading census data dating back to 1960 for all Atlanta MSA counties.

Our initial risk assessment features estimates of how many persons and housing units may have been impacted potentially from significantly severe events occurring at six different time periods (1960–2000 on a decennial basis and also 2006) and consists of simulated tornado, nontornadic convective wind, and hail damage paths placed throughout the three county 'ring' sections. For counties affected by these hypothetical severe events, county population, and housing unit values for each of the six time periods were divided by the respective county areas to produce density values. These density values were multiplied by the simulated damage swath areas for all affected counties, which is the basis for gauging total potential loss numbers throughout the different time periods comprising Atlanta's recent expansion. Naturally, an increase in a region's population corresponds to the presence of more commercial development, public utilities, and automobiles for the respective area. Due to data restrictions, however, this part of the study confines potential loss findings only to housing structures and population estimates.

The damage swaths created for this portion of the analysis were based on damage path dimensions from actual severe events. The hypothetical tornado swaths for this section were based on findings by Brooks (2003), which indicated that the median length and width for an F5 tornado is 54.6 km and 555.5 m, respectively. For rounding purposes, the dimensions of 55 km (length) and 0.5 km (width) are used in this study. Altogether, five simulated tornado damage paths are placed throughout the MSA, with one being placed directly over the Urban Core, two being placed over the Inner Ring, and the final two being placed over the Outer Ring region (Figs. 2, 3).

Hail damage paths created for this section incorporate dimensions of the landmark 2001 "Tristate" hail event, which had a damage path spanning 10–25 km in width and 585 km in length across parts of Missouri (Changnon and Burroughs 2003). Generally, hail damage swaths can affect large portions of city metro regions, so only three damage paths are used for this section and all span the length of the Atlanta MSA. Using the median width of the Tristate hail event (17.5 km), one swath is placed over the Urban Core and the other two are placed to the north and the south of the Atlanta city limits (Fig. 4).

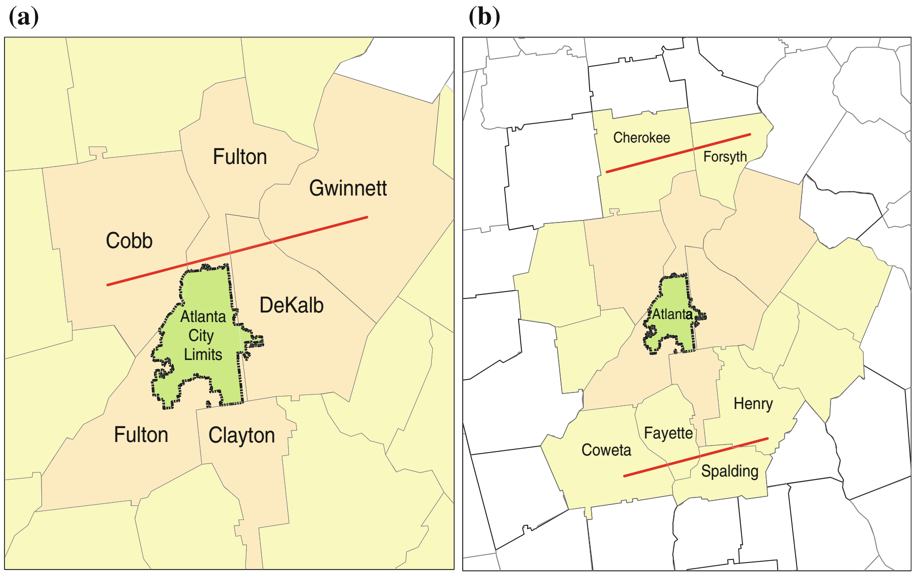

Fig. 2 Atlanta area hypothetical tornado damage scenarios for **a** Urban Core tornado path and **b** Inner Ring tornado paths

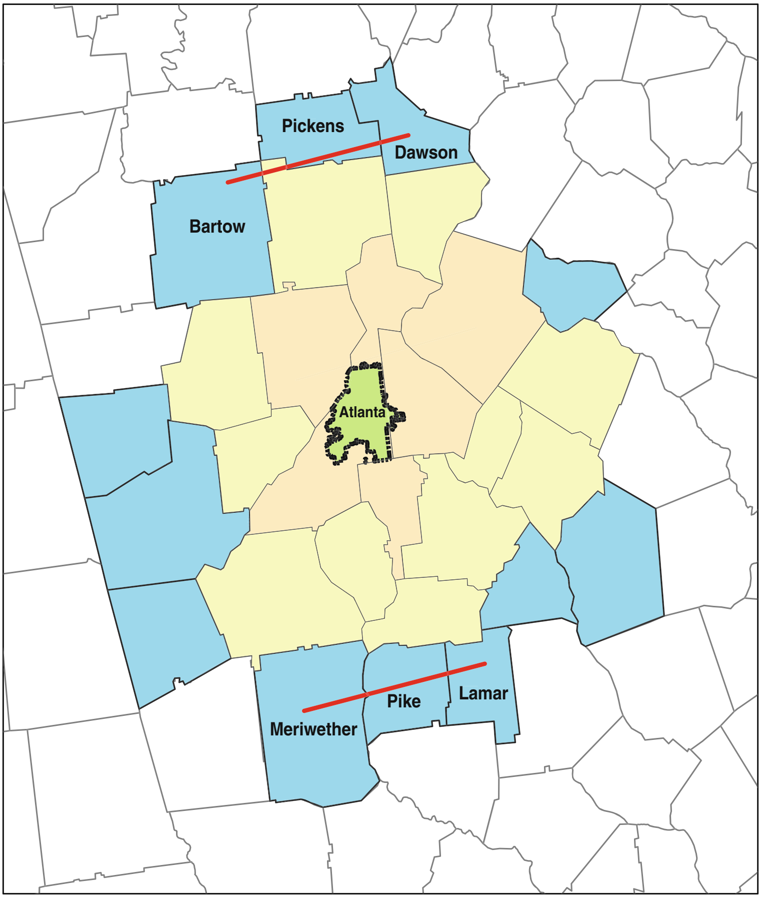

Fig. 3 Atlanta area hypothetical Outer Ring tornado damage path scenarios

Areal coverage of nontornadic convective wind events can be exceptionally large, as the damage path can span distances of several states (Ashley and Mote 2005). Particularly, intense windstorms are classified as derecho events if 50-kt winds are consistently produced over 386 km and if at least three 65-kt wind reports are featured every 64 km (Troutman et al. 2001). Given the limited size of the Atlanta MSA in comparison with the total area affected typically by wind damage events, this section only consists of one wind damage projection created for the study area. The length of the damage path again spans the entire MSA region, whereas the damage width (62.5 km) is based on the mean width of a 2006 Midwest derecho event, which ranged from 50 to 75 km (Przybylinski et al. 2008). Altogether, 17 of the 28 Atlanta MSA counties are affected by this wind event projection.

Our second risk assessment consists of temporal economic factors, which are used to illustrate how an increase in urban development and property appreciation can lead to more costly severe events over time. This approach mirrors a normalization methodology utilized by Pielke et al. (2008), which features the multiplication of event year damage estimates with an adjusted inflation factor, a housing unit adjustment factor, and an adjusted wealth per capita factor (Table 1). All three of these adjustment factors consist of

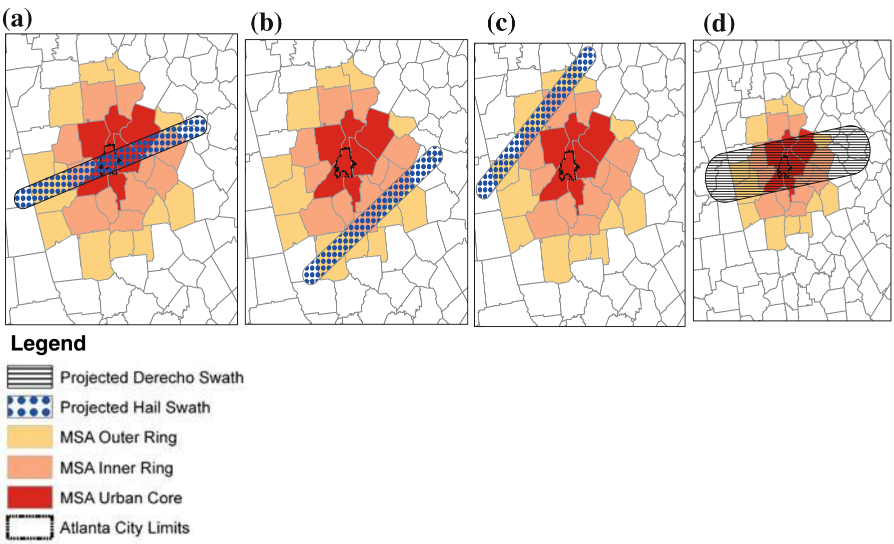

Fig. 4 Hypothetical damage swaths for **a** first hail, **b** second hail, **c** third hail and **d** derecho scenarios

Table 1 Economic adjustments used for 2006 damage estimate factors

Economic adjustor	$D_{2006} = I_{2006/1960} \times RWPHU_{2006/1960} \times HU_{2006/1960}$	
	Featured economic indicator(s)	Featured calculations
Inflation ($I_{2006/1960}$)	Implicit Price Deflator for gross domestic product (IPGDP)	($IPGDP_{2006}/IPGDP_{1960}$)
Real Wealth Per Housing Unit ($RWPHU_{2006/1960}$)	Fixed Assets and Consumer Durable Goods (FACDG) Inflation (I) U.S. Housing Units (USHU)	($FACDG_{2006}/FACDG_{1960}$)/ ($I_{2006}/I_{1960}$)/ ($USHU_{2006}/USHU_{1960}$)
Housing Unit ($HU_{2006/1960}$)	Affected Housing Units in Damage Area (HU)	(HU_{2006}/HU_{1960})

The economic indicators and respective calculations corresponding to these adjustments are listed below, and follow a normalization methodology introduced by Pielke et al. (2008)

economic indicator value ratios of the normalization year with respect to the event year. The adjustment factors and corresponding economic indicators are as follows: inflation (implicit price deflator for Gross Domestic Product or IPDGDP), housing units (impacted housing units), and wealth per capita (fixed assets and consumer durable goods, inflation, and total U.S. housing units). Essentially, the adjustment factors take into account changes in U.S. dollar value, a change in the average number of goods typically owned per U.S. household, and a change in existing housing structures between 1960 and 2006. This approach results in the creation of cost multiplication factors, which project the ratio of 2006 damage estimates from each hypothetical hazard event scenario in comparison with damages incurred in 1960. Values for the IPDGDP and fixed assets indices were retrieved from the Bureau of Economic Analysis (2010a, b), whereas impacted housing unit numbers were retrieved from the “Change in Loss Potential” results, and U.S. housing totals correspond to data found on the U.S. Census Bureau website (2008).

4 Results and analysis

4.1 Changes in potential loss

Large variations in potential exposure are found for the five tornado damage path scenarios analyzed. The most substantial change in potential exposure is found in the Urban Core, as counties comprising this region have experienced the greatest overall increases in population and housing over the past 47 years. Specifically, Gwinnett County has witnessed respective increases in populations and housing units by factors of 17 and 22 throughout this time period (Table 2). This large growth, coupled with DeKalb County's population and housing unit densities tripling since 1960, results in a roughly fourfold and fivefold increase in affected persons and housing unit structures, respectively, from a 2006 hypothetical Urban Core F5 tornado event as opposed to a 1960 event (Table 3).

The Urban Core growth rate is either matched or surpassed by counties comprising the Inner Ring section, as some areas surrounding the city have incurred some of the largest urbanization rates of the region throughout the past five decades. The northern Inner Ring tornado path affects Cherokee and Forsyth counties, which averaged approximately 20 persons km^{-2} in 1960 but had featured population numbers approximately 742% greater (Cherokee County) and 1,115% greater (Forsyth County) by 2006. These high growth rates translate into a tenfold increase in persons affected, and a 13-fold increase in housing units affected by a 2006 hypothetical tornado event as opposed to a 1960 event. The southern Inner Ring damage path similarly affects counties that have observed a moderate amount of development since 1960, although the rate of increase for potential exposure is slightly less for this region. In this case, nearly five times as many persons and six times as many housing units would be impacted by a 2006 tornado event than an event occurring in 1960.

Overall growth rates appear to be relatively more progressive for counties comprising the Outer Ring region, as northern fringe counties have experienced population growth by a factor of about four since 1960, whereas the southern fringe county populations have not even doubled over this same time period. This translates into a hypothetical tornado event in the northern fringe counties affecting approximately 338% more persons in 2006 than in 1960, whereas a 2006 southern fringe event would only affect 71% more persons than in 1960. Although these outer regions of the Atlanta MSA have not experienced the type of explosive development witnessed near the city limits, a distinctly larger number of persons and structures would still nonetheless be potentially impacted by a tornado event occurring in 2006 than in 1960.

Although a disparity in persons and structures has always existed since 1960 between the urban center and the outer metropolitan regions, this gap has widened substantially as the Urban Core and northern portions of the Atlanta MSA have grown far faster than other portions of the study region. For instance, a 2006 major Urban Core tornado strike would affect approximately 2,700% more persons and housing units than an event occurring in the southern sections of the Outer Ring; conversely, a 1960 event would lead to respective percentage differences of approximately 1,000 and 1,100% in persons and homes being potentially impacted. From a spatial standpoint, a short distance today may determine whether a tornado strike would impact a mostly rural environment or whether a costly weather disaster would occur in a highly developed region.

Nontornadic convective wind and hail events affect larger areas than tornado events and will therefore typically have greater damage potential than tornadoes when moving over developed regions (Brooks 2003; Changnon and Burroughs 2003; Przybylinski et al. 2008). Moreover, if an open region were to become developed, the increase in exposed structures

Table 2 Changes in population and housing units for each present-day Atlanta MSA county between 1960 and 2006

	Population			Housing units		
	1960	2006	Change since 1960 (%)	1960	2006	Change since 1960 (%)
Urban Core counties						
Clayton	46,365	268,433	479.0	12,864	103,911	707.8
Cobb	114,174	678,245	494.0	33,135	273,900	726.6
DeKalb	256,782	727,139	183.2	76,875	301,556	292.3
Fulton	556,326	964,281	73.3	172,942	420,947	143.4
Gwinnett	43,541	746,169	1613.7	12,754	274,995	2056.1
Urban Core total	1,017,188	3,384,267	232.7	308,570	1,375,309	345.7
Inner Ring counties						
Butts	8,976	23,080	157.1	3,180	9,060	184.9
Cherokee	23,001	193,676	742.0	6,823	75,379	1004.8
Coweta	28,893	113,863	294.1	8,637	44,238	412.2
Douglas	16,741	118,617	608.5	4,728	46,643	886.5
Fayette	8,199	104,580	1175.5	2,330	38,346	1545.8
Forsyth	12,170	147,855	1114.9	3,883	55,555	1330.7
Henry	17,619	177,116	905.3	4,849	68,270	1307.9
Newton	20,999	90,577	331.3	6,348	35,384	457.4
Paulding	13,101	119,664	813.4	3,920	47,105	1101.7
Rockdale	10,572	79,449	651.5	2,888	30,189	945.3
Spalding	35,404	62,112	75.4	10,538	25,791	144.7
Walton	20,481	78,980	285.6	6,048	30,579	405.6
Inner Ring total	216,156	1,309,569	505.8	64,172	506,539	689.3
Outer Ring counties						
Barrow	14,485	63,044	335.2	4,489	24,640	448.9
Bartow	28,267	90,188	219.1	8,561	36,061	321.2
Carroll	36,451	108,030	196.4	10,954	44,316	304.6
Dawson	3,590	20,526	471.8	1,157	9,484	719.7
Haralson	14,543	28,256	94.3	4,547	11,870	161.1
Heard	5,333	11,331	112.5	1,617	4,844	199.6
Jasper	6,135	13,397	118.4	1,965	5,981	204.4
Lamar	10,240	16,593	62.0	2,977	7,100	138.5
Meriwether	19,756	22,963	16.2	5,575	10,269	84.2
Pickens	8,903	29,217	228.2	2,659	13,463	406.3
Pike	7,138	16,543	131.8	2,132	6,497	204.7
Outer Ring total	154,841	420,088	171.3	46,633	174,525	274.3

from a hail or wind event will likely be larger than from a tornado event, which is reflected in the results stemming from the hypothetical hail and wind damage swaths. The five tornado scenarios for instance indicate that the increase in affected housing unit structures between 1960 and 2006 is in the thousands. The hail and wind scenarios, however, indicate that the increase in affected housing unit structures between 1960 and 2006 is, at the

Table 3 Potential total number of persons and housing units affected from the nine hypothetical severe weather events affecting portions of the Atlanta MSA at six different time periods

Vulnerability factor	Year of event	Vulnerability assessment	Urban Core tornado exposure	Inner Ring Tornado (North) exposure	Inner Ring Tornado (South) exposure	Outer Ring Tornado (North) exposure	Outer Ring Tornado (South) exposure	Hail Scenario 1 (Urban) exposure	Hail Scenario 2 (south) exposure	Hail Scenario 3 (north) exposure	Derecho Scenario exposure
Population	1960	Total affected	4,788	566	899	445	426	399,141	63,289	37,541	1,058,574
		Change since 1960	–	–	–	–	–	–	–	–	–
	1970	Total affected	7,237	775	1,060	525	433	537,742	71,876	45,196	1,440,501
		Change since 1960	51%	37%	18%	18%	2%	35%	14%	20%	36%
	1980	Total affected	9,371	1,286	1,534	687	498	632,496	90,217	62,569	1,790,261
		Change since 1960	96%	127%	71%	54%	17%	59%	43%	67%	69%
	1990	Total affected	12,956	2,161	2,313	993	538	766,938	108,994	94,736	2,318,246
		Change since 1960	171%	282%	157%	123%	26%	92%	72%	152%	119%
	2000	Total affected	17,809	3,939	3,343	1,531	652	997,726	147,509	144,724	3,134,870
		Change since 1960	272%	596%	272%	244%	53%	150%	133%	286%	196%
	2006	Total affected	20,713	5,626	4,291	1,949	730	1,170,367	188,998	188,342	3,708,784
		Change since 1960	333%	894%	377%	338%	71%	193%	199%	402%	250%

Table 3 continued

Vulnerability factor	Year of event	Vulnerability assessment	Urban Core tornado exposure	Inner Ring Tornado (North) exposure	Inner Ring Tornado (South) exposure	Outer Ring Tornado (North) exposure	Outer Ring Tornado (South) exposure	Hail Scenario 1 (Urban) exposure	Hail Scenario 2 (south) exposure	Hail Scenario 3 (north) exposure	Derecho Scenario exposure
Housing Units	1960	Total affected	1,499	165	262	139	123	120,811	18,715	11,305	319,266
		Change since 1960	–	–	–	–	–	–	–	–	–
	1970	Total affected	2,310	259	338	162	138	173,629	23,015	14,278	463,395
		Change since 1960	54%	57%	29%	17%	12%	44%	23%	26%	45%
	1980	Total affected	3,577	479	531	259	172	240,971	31,624	22,631	680,651
		Change since 1960	139%	190%	103%	86%	40%	100%	69%	100%	113%
	1990	Total affected	5,462	830	846	404	203	323,746	40,456	36,562	971,228
		Change since 1960	264%	403%	223%	191%	65%	168%	116%	223%	204%
	2000	Total affected	6,893	1446	1,277	622	250	393,495	56,428	54,952	1,221,017
		Change since 1960	360%	776%	387%	348%	103%	226%	202%	386%	282%
	2006	Total affected	8,292	2,154	1,657	826	296	479,833	75,437	75,894	1,500,018
		Change since 1960	453%	1206%	532%	494%	141%	297%	303%	571%	370%

minimum, in the tens of thousands. This sheer increase in numbers reflects the greater probability of the Atlanta MSA experiencing a potential billion-dollar thunderstorm disaster today as opposed to 1960. If any of the hail or wind scenarios had occurred in this earlier time frame, the results of this study suggest that only the derecho and Urban Core hail event would have likely struck heavily developed regions; conversely, all hail and wind event scenarios appear to affect areas of dense population and housing in 2006, and all have the potential to become costly thunderstorm disasters in this later time frame.

Historically, the largest Atlanta area populations have been located within the Urban Core region. For this reason, the Urban Core hail swath invariably impacts the largest numbers of persons and housing structures for all time periods. The second and third hail swaths, however, pass through some of the same parts of the Atlanta MSA affected by the Inner Ring tornado swaths, which correspond to initially rural areas in 1960 that have witnessed a large amount of development in ensuing years. The second hail scenario impacts a broad region to the south and east of the Urban Core region, which corresponds to areas that have experienced population density increases by a factor of three and housing unit density increases by a factor of four. Of the eight counties affected by this hail scenario, none had featured population densities of at least 100 persons km^{-2} in 1960, while there were three by 2006. The northern hail swath (scenario three) affects areas that have featured some of the fastest growth rates throughout the study region, which include parts of Cherokee County. Once again, none of the six counties affected by this particular hail swath had featured population densities of at least 100 persons km^{-2} in 1960, although this number increases to two by 2006. This particular scenario translates into respective fivefold and approximately sevenfold increases in potential lives and housing structures exposed from a 2006 hail swath event, as opposed to a 1960 event. Additionally, it is worth noting that for all three hail scenarios, the housing unit numbers increase at a faster rate than the population numbers. Using the figures of Table 3, there are approximately 3.3 exposed persons for every affected home for all three hail scenarios in 1960; this ratio decreases to approximately 2.5 persons per home by 2006.

The percentage increases in affected persons and structures found in the derecho scenario are similar to those found in the tornado and hail swath scenarios, as total affected persons and housing units increase by factors of about 3 and 4.7, respectively, between 1960 and 2006. Of the three thunderstorm hazards examined in this study, nontornadic convective winds have the potential to create the largest damage paths (Brooks 2003; Changnon and Burroughs 2003; Przybylinski et al. 2008) and likewise have the potential to affect the largest numbers of persons and structures. These characteristics appear to be consistent with the results of this section, as 17 counties altogether are affected by the derecho projection. While only four of the affected counties have consisted of population densities greater than 100 persons km^{-2} in 1960, this number increases to 11 by 2006. Similarly, the number of affected counties that have at least 50 housing units km^{-2} swells from 2 in 1960 to 13 in 2006. The large areal coverage of this nontornadic convective wind event, coupled with the large growth experienced throughout the Atlanta MSA region, would lead to an estimated 3.7 million persons and 1.5 million housing units affected in 2006, as opposed to only 1 million persons and 300,000 housing units in 1960.

4.2 Economic factors

Damage estimates resulting from hypothetical 2006 severe events in this study are consistently found to be 50–80 times greater than damages that may have resulted from similar magnitude events occurring in 1960 (Table 4). While these estimates can be attributed

Table 4 2006 damage estimate factors for each projected severe event relative to 1960

Severe event	2006 damage normalization factor relative to 1960
Urban Core Tornado Scenario	69.84
1st Inner Ring Tornado Scenario (south)	79.85
2nd Inner Ring Tornado Scenario (north)	164.83
1st Outer Ring Tornado Scenario (south)	30.39
2nd Outer Ring Tornado Scenario (north)	63.21
Hail Swath Scenario 1 (Urban Core)	50.15
Hail Swath Scenario 2 (south)	50.89
Hail Swath Scenario 3 (north)	84.76
Derecho Swath Scenario	59.32

The values listed below follow the normalization methodology illustrated in Table 1 and represent the required multiplication value needed for hypothetical 1960 damage estimates to be adjusted to 2006 estimates for every hazard event scenario

partly to 2006 dollar adjustments and an increase in overall wealth since 1960, the primary driving factor behind these damage factor values is the sheer number of housing structures that have been built since 1960. Areas that were once rural and have undergone development are subjected to much greater potential damage due to the increase in built exposure. This correlation is best illustrated with the five tornado scenarios, which are comprised of damage factor increases ranging anywhere from 30 (the southern Outer Ring scenario, which witnessed minimal growth) to 165 (the northern Inner Ring scenario, which featured substantial growth). Damage estimate factors for large-scale events (e.g., hail and derecho scenarios) are more reflective of how the study area has grown and why recent severe events have been costlier in recent decades than before. The three hail scenarios would affect at least 75,000 structures in 2006, which would result in damage increases anywhere from a factor of 50–85 in comparison with a 1960 event. These figures, however, do not include the almost certain large increases observed in automobiles, commercial real estate developments, and infrastructure in the region since 1960 that would result in potentially higher damage tallies. Loss estimates for the derecho scenario occurring in 1960 would already be sizeable, as an estimated 370,000 housing units would have been impacted. The multiplication of these loss estimates by a factor of 59, coupled with 1.5 million housing structures and additional developments being exposed in 2006, could very possibly result in a billion-dollar thunderstorm disaster.

5 Discussion

From a spatial standpoint, the findings of this study strongly suggest that a distance of several kilometers in some areas will define the difference between a low-impact event and a large multi-million dollar disaster. From a temporal standpoint, the growth of the Atlanta metropolitan region since 1960 has made the area far more susceptible to a costly weather disaster than before. The resulting tallies of impacted persons, housing units, and economic damage factor estimates from the nine hypothetical severe scenarios all suggest the Atlanta region shares a similar scenario to the one outlined by Changnon and Burroughs (2003), which advised that the costly 2001 Tristate hailstorm event likely would have produced minimal damage had it occurred some 40 years earlier when a large proportion of the affected areas had remained undeveloped. The northern Inner Ring hail and tornado scenarios for the Atlanta region appear to complement these circumstances, as hypothetical events traveling over developed regions in 2006 would have likely impacted areas featuring little or no property in 1960. Additionally, when examining temporal economic factors, this study's findings appear to be consistent with those of Hall and Ashley (2008), which illustrates urban sprawl leads to the greater possibility of a modern-day severe event being more costly than in years past.

The results of this study likewise appear to support previous works (Changnon et al. 1997, 2000; Changnon 2008, Schneider et al. 2009), which similarly conclude that the rise in convective weather disasters can largely be attributed to an increase in densely populated regions. The findings of these studies suggest that current urbanization patterns will likely continue exposing far greater numbers of persons and property to intense weather events than in years prior, and costly thunderstorms may no longer be the rare events they may have been in the past.

6 Summary and conclusions

This study conducted a severe thunderstorm hazard vulnerability analysis for the 28 counties comprising the present-day Atlanta MSA. The study region was subdivided into three separate county regions and featured calculations for potential exposure and damage estimates. Results suggest that urban sprawl has increased drastically the Atlanta region's vulnerability to severe weather since 1960. The potential exposure section of this study included nine hypothetical severe hazard projections (five tornado, three hail, one non-tornadic convective wind) throughout the Atlanta MSA and illustrated that severe events occurring in later years corresponded consistently to larger numbers of persons and housing units being potentially exposed. The damage estimate calculations examined changes in inflation, wealth per capita, and housing unit exposure and concluded that 2006 severe events would likely be far costlier than events occurring in 1960.

While this investigation serves primarily to broadly gauge how vulnerability has changed for the Atlanta region as a whole, future studies may focus on Atlanta area communities that may be impacted greatest to weather hazard events. Minority-dominant neighborhoods, for instance, are often unable to access quality resources that are needed for an adequate response to a hazard emergency (Cutter et al. 2003), which was tragically witnessed during the Hurricane Katrina disaster. Additionally, large numbers of the southeastern U.S. populace currently reside in mobile homes, which are exceptionally vulnerable structures during tornado events, and may partially account for the large numbers of tornado fatalities typically found in this region (Ashley 2007; Sutter and Simmons 2010). Finally, Atlanta geographically lies in a region susceptible to heavy rainfall from organized convection, summertime pulse convection, and landfalling tropical systems. The events of September 2009 serve as a reminder that flooding hazards are the second deadliest weather-related killer behind only heat waves (Ashley and Ashley 2008; Shepherd et al. 2010). Future studies comprising these topics may provide a better understanding of weather hazard vulnerability for the Atlanta MSA region.

In closing, this investigation illustrates how U.S. urban settlement patterns in the late twentieth and early twenty-first Centuries, juxtaposed with natural hazard exposure, could lead to costly disasters and high numbers of potential casualties. Recent advancements in the understanding of severe thunderstorms have arguably made the U.S. society far safer today to these hazards. Despite progress with detection, warning, and mitigation systems, larger numbers of the general public will now be required to act if a dangerous situation were to loom. This will challenge system effectiveness in reducing future hazard-induced casualties and damages. By providing insight into thunderstorm exposure within a rapidly expanding urban environment, this study provided a foundation to monitor future urban vulnerabilities and their adjustments. These methods could be employed to assist forecasters, emergency management, and the public in the mitigation of future severe thunderstorm events in highly developed urban cores and suburbia.

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