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Urban-induced thunderstorm modification in the Southeast United States

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Abstract This study provides the first climatological synthesis of how urbanization augments warm-season convection among a range of cities in the southeastern U.S. By comparing the location of convection in these cities and adjacent control regions via high-resolution, radar reflectivity and lightning data, we illustrate that demographic and land-use changes feed back to local atmospheric processes that promote thunderstorm formation and persistence. Composite radar data for a 10-year, June–August period are stratified according to specific "medium" and "high" reflectivity thresholds. As surrogates for potentially strong (medium reflectivity) and severe (high reflectivity) thunderstorms, these radar climatologies can be used to determine if cities are inducing more intense events. Results demonstrate positive urban amplification of thunderstorm frequency and intensity for major cities. Mid-sized cities investigated had more subtle urban effects, suggesting that the urban influences on thunderstorm development and strength are muted by land cover and climatological controls. By examining cities of various sizes, as well as rural counterparts, the investigation determined that the degree of urban thunderstorm augmentation corresponds to the geometry of the urban footprint. The research provides a methodological template for continued monitoring of anthropogenically forced and/or modified thunderstorms.

1 Introduction

Anthropogenic land use/land cover (LULC) changes modulate meteorological and/or climate forcings at the local (e.g., Dixon and Mote 2003; Stallins and Bentley 2006; Hand and Shepherd 2009), regional (e.g., Mahmood et al. 2006; Carleton et al. 2008; Fall et al. 2009; Mahmood et al. 2010), and global scales (e.g., Chase et al. 2000; Feddema et al.

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2005). The Intergovernmental Panel on Climate Change (Trenberth et al. 2007), National Research Council (NRC 2005, 2010), and U.S. Climate Change Science Program (CCSP 2003) have emphasized the importance of LULC changes on influencing human-environment systems. The most dramatic LULC modification of the natural environment is arguably urban development. Currently, over 50% (82%) of the world (U.S.) population lives in an urban area, and this proportion is predicted to grow beyond 70% (90%) by 2050 (United Nations 2007). Urban weather hazards are identified by the U.S. Weather Research Program as a critically important area of research in consideration of the large economic liabilities and enhanced human vulnerabilities embedded within densely populated regions (Dabberdt et al. 2000; Dilley et al. 2005; Borden et al. 2007).

There is a large body of literature that illustrates that urban areas modify their weather and climate (Shepherd 2005; Shepherd et al. 2010). These studies have focused almost exclusively on temperature (Kalnay and Cai 2003; Hale et al. 2008) and precipitation (Huff and Changnon 1973; Shepherd et al. 2002; Kaufmann et al. 2007; Kishtawal et al. 2010). These atmospheric properties are secondary phenomena of the higher heat content, increased surface roughness, and boundary layer instability associated with urban areas. A more direct causal phenomenon indicative of how urban areas modify weather is convection—the dynamic process by which updrafts initiate and lead to cloud condensation, hydrometeor formation, and cloud electrification. With the advent and improvement of remote sensing platforms over the last two decades, thunderstorm climatologies of major metropolitan areas have been developed through the employment of cloud-to-ground lightning data (Westcott 1995; Orville et al. 2001; Stallins and Rose 2008), space-borne precipitation radar data (Shepherd et al. 2002), and, recently, National Weather Service WSR-88D radar data (Mote et al. 2007; Bentley et al. 2010). However, no long-term, multi-scaled geographic investigations of urban-enhanced convective storms exist. In addition, none of these prior studies incorporate "controls," regions to reveal whether urban convective anomalies are reproduced in rural regions. A major question in urban weather and climate research is how much cities vary in their propensity to modify local convection.

Our research illustrates how urbanization augments warm-season thunderstorm activity among a range of cities in the southeastern U.S., a region that experiences diurnally forced convection during the warm-season with only occasional synoptic-scale forcing for ascent (Court and Griffiths 1981; Bentley and Stallins 2005; Bentley et al. 2010). Urbanization contributes to a variety of processes that may lead to enhancement of thunderstorms; these mechanisms include urban heat island (UHI) dynamics, enhanced localized forcing due to increased surface roughness, and elevated production of aerosols and, subsequent, cloud condensation nuclei (see Shepherd (2005) and Shepherd et al. (2010)) for an overview of these phenomena). By comparing the timing, location, and intensity of convection in cities and adjacent control regions, we analyze how these demographic and LULC changes feed back to strong and severe thunderstorms. Furthermore, given predicted increases in thunderstorm frequency and severity under a scenario of anthropogenic global warming (Price and Rind 1994; Trapp et al. 2009), urban thunderstorms are economically relevant to weather and hazard planning policy.

2 Methods

The seven locations in the southeastern U.S. chosen for investigation comprise five cities of various sizes with the addition of two control, or null, regions that are predominantly rural (Table 1). Although each location is unique in terms of LULC, the sites were chosen because of similarities in terrain and the lack of persistent local boundaries (e.g., sea breeze) that would exert a major control on convective storm development. In addition, we limited our analyses to the warm-season months of June through August; the part of the year when the Southeast U.S. is largely absent synoptic-scale forcing and is dominated by a maritime tropical airmass associated with weakly forced, diurnally driven convection (Court and Griffiths 1981; Dixon and Mote 2003; Stallins and Bentley 2006). We hypothesize that the formation of isolated, airmass storms in these conditions across our domain will be coupled to LULC, including urban land use effects. In order to assure that we were assessing synoptically benign days associated with only maritime tropical airmasses, we employed the spatial synoptic classification (SSC) dataset (Sheridan 2002). The SSC is a synoptic weather-typing tool that employs four-times daily observations of temperature, dew point, pressure, and cloud cover to delineate seven different weather types to characterize the daily air mass at a particular location. Only city-specific days where the SSC indicated a moist tropical (MT), moist tropical plus (MT+), or moist tropical plus-plus (MT++) airmass were examined (Table 1). Because our rural control locations were not available in the SSC database, we used the closest SSC identified city (i.e., for Starkville, MS we used Meridian, MS; for Heflin, AL we used Birmingham, AL).

In order to examine urban effects on thunderstorm frequency and magnitude across these locations, we assessed 10 years (1997–2006) of NOWrad™ national composites of National Weather Service WSR-88D reflectivity data (Crum and Alberty 1993) produced by WSI Corporation. These data have temporal, spatial, and reflectivity resolutions of 5 min, 2 km × 2 km, and 5 decibels of equivalent radar reflectivity (or dBZ) , respectively, and illustrate the largest reflectivity measured in a 5-minute interval by any radar scan in a column above each grid cell. The data are quality controlled by WSI to filter artifacts such as ground clutter. Our analyses focus on only those events that meet or exceed 40 dBZ, which we define as the minimum reflectivity for a convective element, or thunderstorm. This threshold is a common discriminator between convective and stratiform precipitation (Gamache and Houze 1982; Falconer 1984; Rickenbach and Rutledge 1998; Parker and Knievel 2005). In order to assess the intensity of thunderstorms, we examined the spatiotemporal constituents of three reflectivity categories: 1) the amount of time that a grid cell experienced 40, 45, or 50 dBZ, which illustrates the approximate reflectivity magnitudes of a modest, nonsevere thunderstorm, 2) the amount of time that a grid cell

Table 1 Characteristics of Metropolitan Statistical Areas and control regions examined, ranked by population (http://www.census.gov/population/www/metroareas/metroarea.html). Buffers in km

MSA or rural control	Population (1990)	Population (2000)	Population (2009 est.)	1990–2009% Change	Urban Buffer	Rural Buffer	Moist Tropical Days Examined
Atlanta, GA	2,959,950	4,112,198	5,475,213	84.98%	40	100	362
Memphis, TN	1,007,306	1,135,614	1,304,926	29.55%	35	87.5	471
Birmingham, AL	840,140	921,106	1,131,070	34.63%	30	75	429
Jackson, MS	395,396	440,801	540,866	36.79%	25	62.5	427
Montgomery, AL	292,517	333,055	366,401	25.26%	25	62.5	441
Starkville, MS control	–	21,869	–	–	31	77.5	438
Heflin, AL control	–	3,002	–	–	31	77.5	429

experienced greater than 50 dBZ, which is associated with strong-to-severe thunderstorms that can produce urban flash flooding, lightning, large hail, and microbursts, and 3) the "sum" total of the medium and high reflectivity events, or the total amount of time that a grid cell experienced greater than 39 dBZ. The reflectivity categories are examined using the dual criteria of minutes observed (i.e., number of 5-minute scans that meet the dBZ criterion, or "occurrences") and the convective day metric (i.e., number of days that meet the dBZ criterion).

We supplemented our radar analyses for the Atlanta, GA Metropolitan Statistical Area (MSA) with 10 years (1997–2006) of cloud-to-ground lightning data acquired from the U.S. National Lightning Detection Network (NLDN) produced by Vaisala Corporation. In order to eliminate intracloud flash contamination, we removed positive polarity flashes <10 kiloamps from 1997–2001 and positive polarity flashes <15 kiloamps from 2002–2006 (Cummins et al. 1998; Wacker and Orville 1999; Rudlosky and Fuelberg 2010). The lightning strike data were gridded on the same 2 km×2 km grid as the radar data and analyzed using two metrics: flash counts (total number of flashes per grid cell) and flash day counts (number of days in which at least one cloud-to-ground lighting flash occurred per grid cell).

Urban versus rural LULC delineations vary across remote sensing platforms, LULC datasets, and spatiotemporal resolutions. To examine a variety of definitions of urban and rural areas, and their influences on our results, we used three separate methods to discriminate between these fundamental LULC types on the aforementioned 2 km×2 km base grid across the domains (Fig. 1).

First, we employed the National Land Cover Database (USGS 2001a; hereafter, NLCD), which contains standardized land cover components using Landsat 5 and 7 data. In particular, we identified the urban region of our largest cities (Atlanta, Memphis, and Birmingham) that contained four of NLCD's land cover classifications, including: Developed, Open Space (21), Developed, Low Intensity (22), Developed, Medium Intensity (23), and Developed, High Intensity (24). Each 2 km×2 km grid cell that contained an areal coverage of these four NLCD classifications greater than 49% was considered "urban"; cells that contained less than or equal to this critical threshold were considered "rural". This method produced a large urban polygon near the center of the metropolitan regions, but also highlighted some areas outside of the relative urban core. Thus, any extraneous "urban" cells that were not a part of the primary polygon containing the urban core were excluded from the urban delineation. Those rural areas contained within the urban core demarcation (i.e., rural grid cells enclosed in the larger urban polygon) were considered urban due to their containment in the larger urban outline. This conterminous urban method provides a conservative estimate of the urban core regions of our largest MSA regions and is hypothesized to capture the areas where warm-season urban effects are strongest.

Next, we used the USGS's (2001b; hereafter, USGS) urban areas vector layer dataset, which illustrates areas of built-up land where large populations exist. The urban core was assessed in the same manner as above; essentially, if an individual grid cell contained greater than 49% of this vector classification, it was considered urban. This method provides an irregular polygon that outlines the urban footprint of the cities.

Finally, we employed a set of simple geometric buffer constructions based on spatial satellite examination of recent development trends to illustrate the urban cores for all cities examined, as well as the two rural controls (Table 1). In Atlanta's case, we delineated the

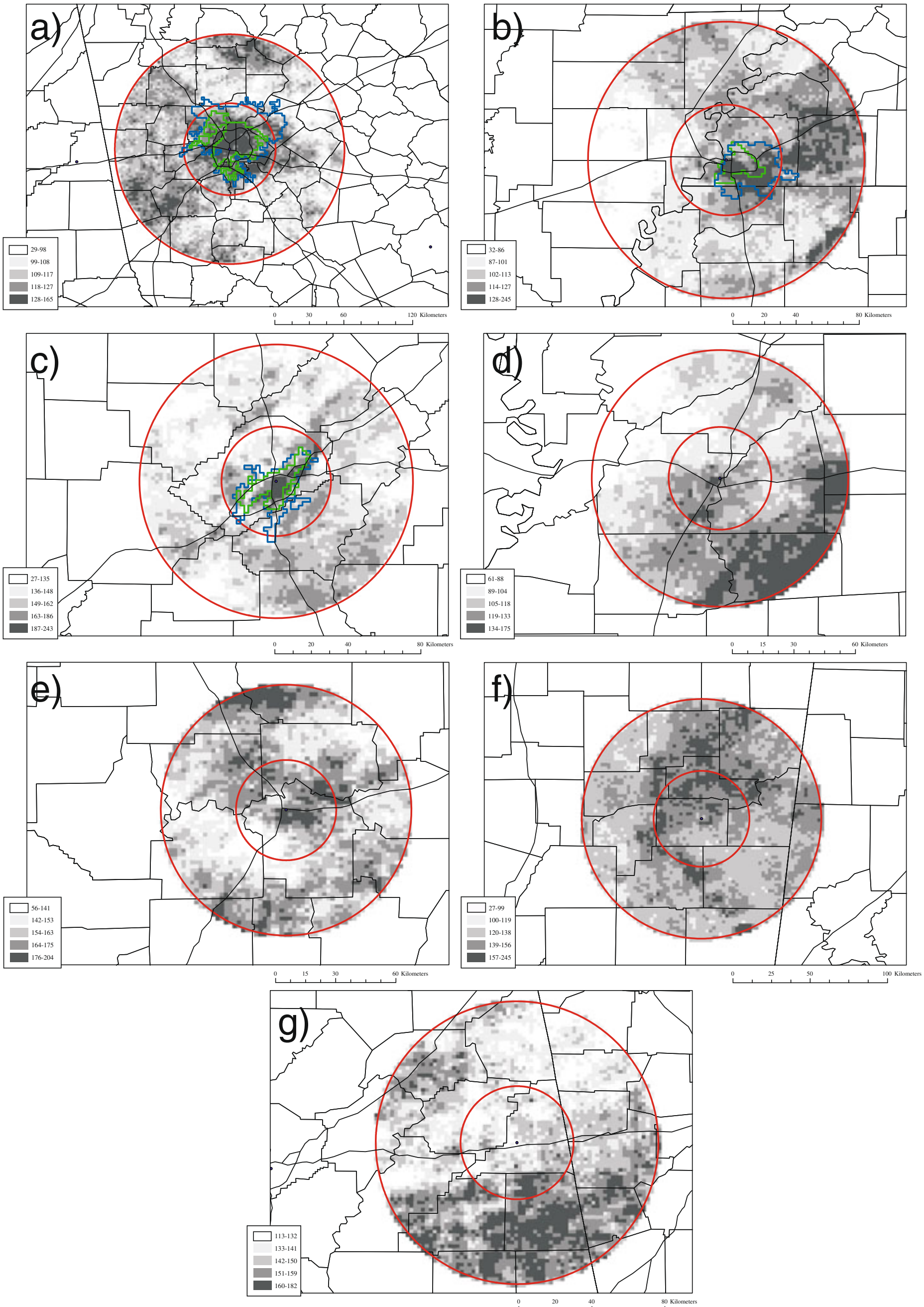

Fig. 1 Frequency of June–August medium and high reflectivity days, or total days ≥40 dBZ in each 2-km grid cell, for the 10-year period of record for (**a**) Atlanta, (**b**) Memphis, (**c**) Birmingham, (**d**) Jackson, (**e**) Montgomery, (**f**) Starkville control, and (**g**) Heflin control. Red circles correspond to urban-rural buffers outlined in Table 1. For (**a**–**c**), the blue (green) lines represent NLCD (USGS) urban delineations

urban region as the area contained within an area swept out by a 40 km radius from city center. Memphis (Birmingham) has a smaller urban footprint; therefore, the urban footprint was illustrated as a circle with a 35 km (30 km) radius. The control regions had surrogate urban areas defined by a 31 km buffer, which was the average radius of the five urban buffers used for the cities.

Maritime tropical airmassess typically have nominal background synoptic flow, which will tend to lessen any drift effects from urban-initiated or enhanced thunderstorms (e.g., downwind city enhanced thunderstorm maximums found in rural buffer zones). Results presented suggest that urban influences on convection are reduced considerably as distance from city center increases.

The radar reflectivity (as well as lightning for Atlanta) climatology was constructed for city-specific buffers and urban vs. rural outlines for each location. These varying scales of analysis were used to resolve population and land cover influences on convective storm development within and surrounding urban areas.

3 Results

3.1 Spatial analysis

Visual analysis of the warm-season, maritime tropical convective reflectivity characteristics across cities and controls revealed a trichotomy in convective enhancement due to urban influences (Figs. 1 and 2). The largest MSAs—Atlanta, Birmingham, and Memphis—had medium, high, and total (medium+high) reflectivity occurrence and day hotspots clustered within and near the urban cores, while analyses of the smaller cities (Jackson and Montgomery) suggest a more indistinct urban influence. The control regions (Heflin and Starkville) illustrate reflectivity trends that have little to no spatial correlation with surrogate city centers. This initial spatial interpretation suggests that: 1) large cities do instigate thunderstorm formation as well as augment convective intensity; and 2) the scale and distribution of the city footprint is an important factor in determining urban influences on thunderstorm formation and sustenance. Urban spatial extent has been suggested as an important gauge of UHI magnitude (Huff and Changnon 1973; Oke 1981, 1982; Bentley et al. 2010); however, Westcott (1995) noted that there was more city-to-city variability in lightning enhancement than what could be explained by size alone. Analyses of radar reflectivity trends suggest that cities must be of sufficient size to identifiably increase thunderstorm frequencies and that, ultimately, there appears to be a tipping point at which humid subtropical cities and their heating nodes, roughness factors, and/or aerosol production become significant in augmenting convection.

Atlanta and Birmingham's reflectivity hotspots have different spatial densities that appear to be controlled by the distribution of population and development across the two urban landscapes. Birmingham has a more concentrated urban core in comparison to Atlanta's well-known sprawling quality (Lo and Yang 2002). These characteristics appear to be manifested in the thunderstorms amplified by the cities. Birmingham has a much more concentrated occurrence and day reflectivity hotspot, with Atlanta revealing a broad elevated distribution of enhanced reflectivity across the urban core and surrounding suburbia. Birmingham's unique orography has shaped both urban and suburban development trends and appears to influence the area's thunderstorm distribution. The Alabama city is flanked by long, parallel mountain ridges of modest height (approximately

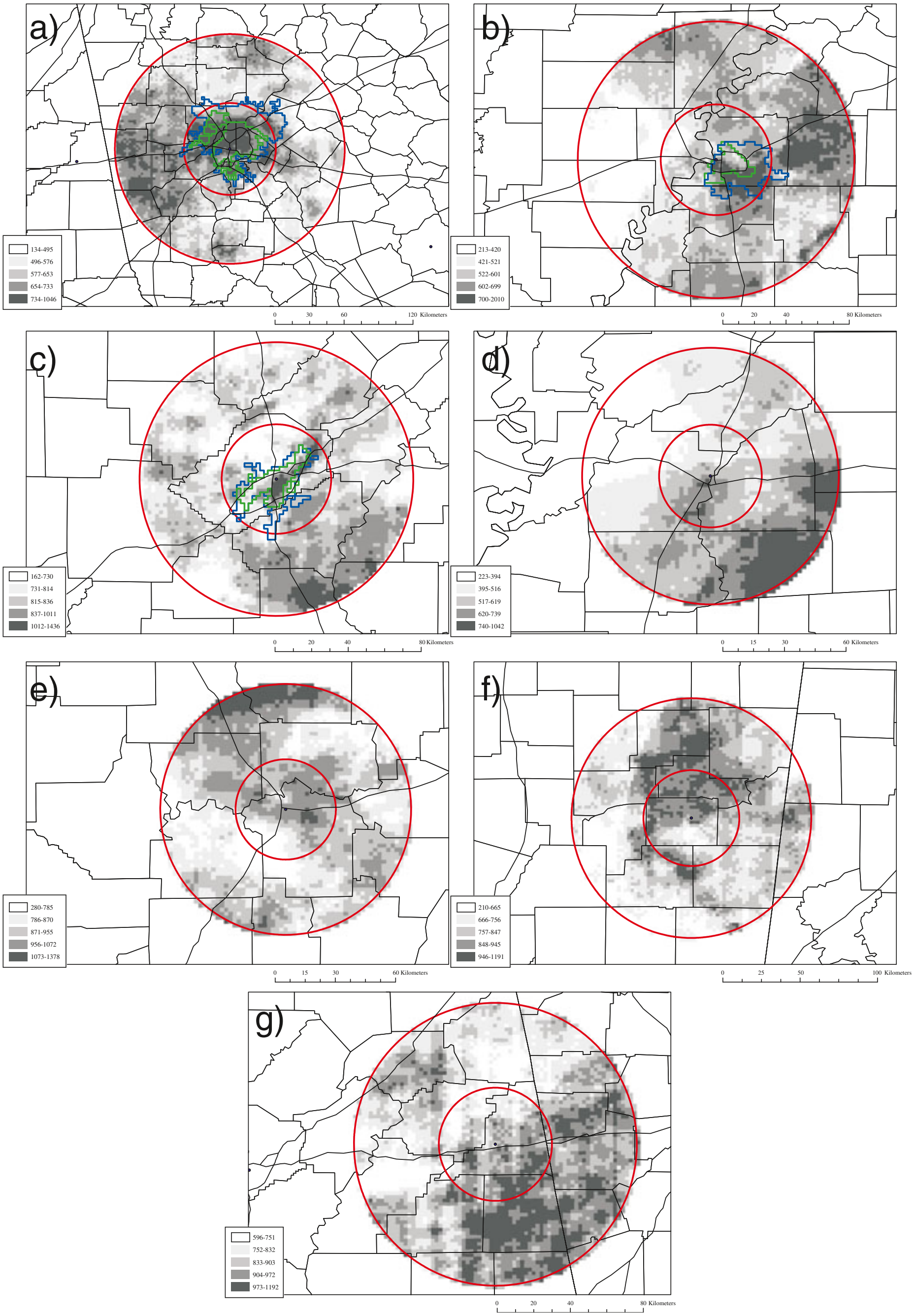

Fig. 2 As in Fig. 1, except frequency of June–August medium and high reflectivity occurrences, or total number of 5-minute occurrences ≥40 dBZ in each 2-km grid cell, for the 10-year period of record

90–170 m above central business district (CBD) elevation) that appear to be local sources of thunderstorm initiation. The convective hotspots found in the various reflectivity data parallel not only the urban core, but also the Red Mountain area immediately southeast of the Birmingham CBD. It is difficult to decipher whether urbanization, orography, or both are the dominating influence(s) in creating the enhancement found in the immediacy of Birmingham. However, similar parallel ridgelines in the east and southeast of the Birmingham MSA, as well as the comparatively high Talladega Mountains (found in the eastern Birmingham and western Heflin domains), appear to exert little influence on the reflectivity trends. Thus, while it is possible that orography could modulate the urban-enhancement found in Birmingham, it is hypothesized to have a geographically contingent effect in comparison to urban LULC.

Converse to Atlanta's sprawl development mode, Memphis' population expansion and, therefore, urban thunderstorm influences are sharply confined to the urban core with a broad decreasing enhancement that slopes eastward away from the CBD. This enhancement pattern parallels the underlying urbanization and suburbanization trends found in this MSA, which are largely confined to the city center and eastward due to the Mississippi River and associated agriculturally rich flood plain encountered directly west of the CBD.

Spatial reflectivity characteristics of the Jackson and Montgomery regions demonstrate complex local and/or regional controls on thunderstorms. Analysis reveals that the urban area itself appears large enough to exhibit some influence on thunderstorm patterns—evidenced especially in Montgomery's total reflectivity days, but also more subtly in Jackson's few high-activity pixels within and near the city center. However, the urban enhanced dynamics appear not sufficient enough to overcome other local/regional processes (e.g., LULC effects, ambient atmospheric environment characteristics at initiation, etc.) to make urbanization a dominant influence on thunderstorm formation and sustenance. This leads to a noisier solution in the medium city climatologies as individual thunderstorm occurrences and days likely contain an urban signature combined with, and possibly overshadowed by, other localized forcing mechanisms modulating the convection.

One of the major shortcomings of contemporary urban weather modification research has been the lack of use of null, or control, regions (Lowry 1998; Shepherd 2005)—i.e., rural area centroids removed from the influence of city centers and suburban growth. These predominantly rural controls—in our investigation, Heflin and Starkville—permit the validation of the extent to which convective anomalies witnessed in proximity to urban centers are reproduced in rural regions, whether by natural variability or other environmental features such as topography. Essentially, do the hotspots found in large cities like Atlanta replicate in control regions, which, if so, calls into question the argument validity of the urban influence of convection.

Visually, the reflectivity patterns found in Heflin, which straddles Atlanta and Birmingham MSAs, reveal no singular hotspots centered near the surrogate urban core. Starkville has a broad maximum to the north as well as a spine of higher reflectivity that appears tied specifically to non-urban LULC effects. In particular, the narrow north-south correspondence of the physiographic-distinct land covers of Upper Coastal Plain, Blacklands, and Interior Flatwoods in the Starkville region (Brown and McCann 2004) appear to be the dominating influence on the warm-season convective climatology. Further analysis of this region's physiographic influence on convection will be required to determine how low-level circulations and convergence (Segal and Arritt 1992; Brown and Arnold 1998; Carleton et al. 2008) induced by unique land-cover-type boundaries may be augmenting the convective climatology. Ultimately, initial conclusions from the mid-sized city spatial analysis is a reminder that urbanization is only a single, albeit increasingly important, variable in determining the complex distribution of thunderstorms.

3.2 Statistical comparisons

To objectively assess the initial findings revealed in the spatial analysis, we examined the statistical significance for differences in the mean (median) reflectivity characteristics using the independent-samples *t*-test (Mann-Whitney *U* Test) between the rural and urban regions across the seven domains. Significance testing ($\alpha=0.05$) across various medium, high, and sum reflectivity categories revealed that, in most instances, large cities had statistically significant increases in warm-season thunderstorm occurrences and days in comparison to their rural counterparts. We examined this significance using the three separate methods for defining urban and rural areas as discussed in Section 2 (Tables 2 and 3).

All three of the largest cities examined (Atlanta, Birmingham, and Memphis) had statistically significant increases across all urban delineations except for a single case—medium occurrences in the Birmingham area using the buffer method, which revealed a significant decrease in medium reflectivity occurrences (t=−3.49; $p=0.000$). Further analysis of the spatial distribution of medium occurrences revealed that this outlier may be caused by two reasons: 1) the urban buffer demarcation of 30 km from city center may be too generous for this more focused population center, and 2) an area of enhanced medium reflectivity occurrences found in the southeast quadrant of the rural domain tended to increase the rural reflectivity contribution. It may also be that the particular nature of aerosols in Birmingham—specifically, their size and concentration—may result in a different distribution of medium and high reflectivity occurrences (van Den Heever and Cotton 2007). This significant decrease in the Birmingham medium occurrence data was not reflected in the high occurrences, but did manifest when medium and high occurrence

Table 2 Results from independent samples *t*-test. No significance in difference of means shaded gray; significantly lower urban reflectivity characteristic shaded blue; significantly higher urban reflectivity not shaded

City (urban delineation)	Medium Occurrences		High Occurrences		Medium+High Occurrences		Medium Days		High Days		Medium+High Days	
	t	P	t	P	t	P	t	P	t	P	t	P
Atlanta (NLCD)	31.25	0.000	26.23	0.000	32.22	0.000	27.18	0.000	28.42	0.000	32.11	0.000
Atlanta (USGS)	27.33	0.000	24.78	0.000	28.33	0.000	26.61	0.000	24.48	0.000	30.16	0. 000
Atlanta (Buffer)	35.37	0.000	36.12	0.000	37.16	0.000	30.73	0.000	37.61	0.000	38.48	0.000
Memphis (NLCD)	19.02	0.000	15.34	0.000	19.37	0.000	19.76	0.000	18.43	0.000	24.03	0.000
Memphis (USGS)	9.665	0.000	84.48	0.000	9.88	0.000	11.53	0.000	11.3	0.000	15.38	0.000
Memphis (Buffer)	10.01	0.000	23.18	0.000	11.29	0.000	15.65	0.000	22.15	0.000	19.47	0.000
Birmingham (NLCD)	3.955	0.000	18.03	0.000	6.16	0.000	19.55	0.000	15.4	0.000	20.62	0.000
Birmingham (USGS)	6.409	0.000	17.25	0.000	8.29	0.000	19.88	0.000	15.36	0.000	20.85	0.000
Birmingham (Buffer)	-3.49	0.000	12.48	0.000	-1.35	0.176	19.41	0.000	11.93	0.000	19.09	0.0001
Jackson (Buffer)	-0.36	0.719	-0.32	0.753	-0.36	0.717	2.665	0.008	-1.20	0.230	1.94	0.520
Montgomery (Buffer)	4.407	0.000	11.36	0.000	5.34	0.000	0.74	0.460	11.15	0.000	4.87	0.000
Starkville (Buffer)	20.04	0.000	19.12	0.000	20.69	0.000	13.26	0.000	21.9	0.000	18.0	0.000
Heflin (Buffer)	2.149	0.320	-12.8	0.000	0.89	0.376	7.18	0.000	-11.7	0.000	0.89	0.376

Table 3 Results from Mann-Whitney *U* Test, which is employed to determine if the two distributions (medians) are equal. No significance in difference of medians shaded gray; significantly lower urban reflectivity characteristic shaded blue; significantly higher urban reflectivity not shaded

City (urban delineation)	Medium Occurrences		High Occurrences		Medium+High Occurrences		Medium Days		High Days		Medium+High Days	
	Z	P	Z	P	Z	P	Z	P	Z	P	Z	P
Atlanta (NLCD)	-28.14	0.000	-23.30	0.000	-28.68	0.000	-25.03	0.000	-24.70	0.00	-27.99	0.000
Atlanta (USGS)	-24.31	0.000	-20.88	0.000	-24.85	0.000	-23.69	0.000	-20.74	0.00	-25.38	0.000
Atlanta (Buffer)	-32.07	0.000	-30.90	0.000	-33.25	0.000	-28.50	0.00	-32.21	0.000	-33.85	0.000
Memphis (NLCD)	-16.56	0.000	-21.86	0.000	-16.93	0.000	-19.76	0.000	-14.37	0.000	-20.70	0.000
Memphis (USGS)	-7.48	0.000	-8.69	0.000	-7.81	0.000	-11.53	0.000	-8.69	0.000	-12.12	0.000
Memphis (Buffer)	-7.74	0.00	-21.86	0.000	-9.25	0.000	-15.65	0.000	-21.86	0.000	-18.63	0.000
Birmingham (NLCD)	-2.27	0.023	-11.83	0.000	-3.88	0.000	-12.83	0.000	-10.86	0.000	-13.23	0.000
Birmingham (USGS)	-4.37	0.000	-9.74	0.000	-5.48	0.000	-12.51	0.000	-9.86	0.000	-12.46	0.000
Birmingham (Buffer)	-4.16	0.000	-8.26	0.000	-2.34	0.019	-14.52	0.000	-9.00	0.000	-14.08	0.000
Jackson (Buffer)	-0.23	0.822	-0.36	0.723	-0.17	0.864	-2.64	0.008	-0.41	0.685	-2.04	0.041
Montgomery (Buffer)	-7.14	0.000	-10.82	0.000	-7.97	0.000	-1.16	0.116	-10.43	0.000	-6.11	0.000
Starkville (Buffer)	-19.75	0.000	-17.29	0.000	-20.07	0.000	-13.16	0.000	-19.33	0.000	-17.00	0.000
Heflin (Buffer)	-2.15	0.032	-12.58	0.000	-9.71	0.331	-7.39	0.000	11.59	0.000	-9.95	0.000

data were summed. In this particular sample, there was not enough evidence to conclude that the mean rural and urban event occurrences ≥40 dBZ were statistically distinguishable.

The smaller cities of Jackson and Montgomery had a range of results. Across most reflectivity categories, Jackson rural and urban buffers had no significant differences in the means or medians, which confirms the initial hypotheses that the Jackson urban area is perhaps too small to modify thunderstorms or is masked by other circulations and convergence mechanisms induced by non-urban LULC effects. While Jackson is relatively close (250 km) to the Gulf of Mexico, there appears to be little evidence that the sea-breeze effect (Gibson and Vonder Haar 1990; Smith et al. 2005) extends this far inland recurrently and, therefore, is influencing the climatology found herein.

Montgomery has statistically greater reflectivity counts in its 25 km urban buffer in comparison to the surrounding rural region except for the category of medium days ($t=0.74$, $p=0.460$). This statistical evidence reconfirms the apparent moderate urban influence identified visually, suggesting that despite the cities relatively small size, it may impact warm-season thunderstorm frequency.

Heflin and Starkville have differing statistical results, which must be weighed against visual analyses of the reflectivity climatology to confirm the lack of urban influence. In Heflin's case, statistical tests suggest that the frequency of various reflectivity characteristics for the surrogate urban area and rural region were not statistically distinguishable or had significantly lower "urban" reflectivity in comparison to the rural region. This result implies that the Heflin region exemplifies no urban influence, providing support to the hypothesis that urbanization influences the thunderstorm climatology in and around cities of sufficient size. Across all various reflectivity characteristics, Starkville's surrogate urban sphere was significantly higher compared to its rural counterpart. This result would initially appear to be counter to the hypothesis that urbanization does augment thunderstorm frequencies and intensity. A visual inspection of the reflectivity climatologies suggests that the differences found are not linked to urbanization effects since urbanization is minimally developed. Locally variable physiography may, in this case, have produced the statistical anomaly.

3.3 Graphical analyses of urban convection

Employing a set of scatterplots and quadratic line fits further elucidates the urban influence on thunderstorm occurrences across the domains. In particular, we examined the frequency of various reflectivity thresholds, as well as lightning strikes for Atlanta, versus distance from city center to appraise the urban effects on thunderstorms. A concave curvilinear form sloping away from a city center supports the hypothesis of urban enhanced thunderstorms in and near city center.

The resulting medium and high, or total, reflectivity scatterplots and line fits confirm the urban effects on thunderstorm frequency evident in our other analyses (Fig. 3). We present only the total reflectivity scatterplots of Atlanta using the NLCD demarcation, but provide comprehensive graphical summary of the line fits for all cities and null regions in Fig. 4. Both Atlanta occurrence and day scatterplots exemplify frequency counts that slope dramatically away from the high values near the CBD to the comparatively low values found across the rural area. The Atlanta buffer delineation of 40 km, as well as NLCD-based urban definition, appear to separate well the urban and rural frequency shifts since the slopes of the quadratic fits appear to lessen near the urban/rural separation.

Atlanta and Memphis slopes are some of the steepest found across the domains, which implies that the urban effects on convection in these cities are the most dramatic. Birmingham continues this large-city tendency for total days, but is inconclusive for occurrences. Again, this gradual slope is due to the enhanced counts found in southeast Birmingham domain for medium occurrences, which is reflected as a flat line fit (not shown) for this classification. Individually, Birmingham's medium days, high days, and high occurrence data (not shown) reveal steep slopes of elevated reflectivity counts near the city center, and reduced counts across the rural domain.

The mid sized cities Montgomery and Jackson continue to exhibit mixed results in terms of slope magnitude, but do illustrate a broad decrease in reflectivity counts away from the city centers. Montgomery slopes for medium plus high days and events are more substantial; in fact, the Montgomery total occurrences is the steepest slope of all domains. Both Starkville and Heflin curves are either flat or convex, which illustrate a different distribution when compared to the city domains. Despite Starkville's decreasing slope from "city" center, its diminishing trend and lack of substantial concavity does not fit the pattern found in the urban cases. Heflin is uniquely flat for reflectivity occurrences, and slope ascends from the surrogate city center for day counts, an atypical characteristic that supports the lack of urban influence near the domain's center.

3.4 Percentage increase in thunderstorms

Comparing the means of the urban and rural reflectivity frequencies illustrates the proportional increases, or decreases, in thunderstorms across domains (Table 4). Atlanta and Memphis featured percentage increases in medium, high, and total reflectivity frequencies across the urban areas. In both cities, the largest percentage increases (≥36%

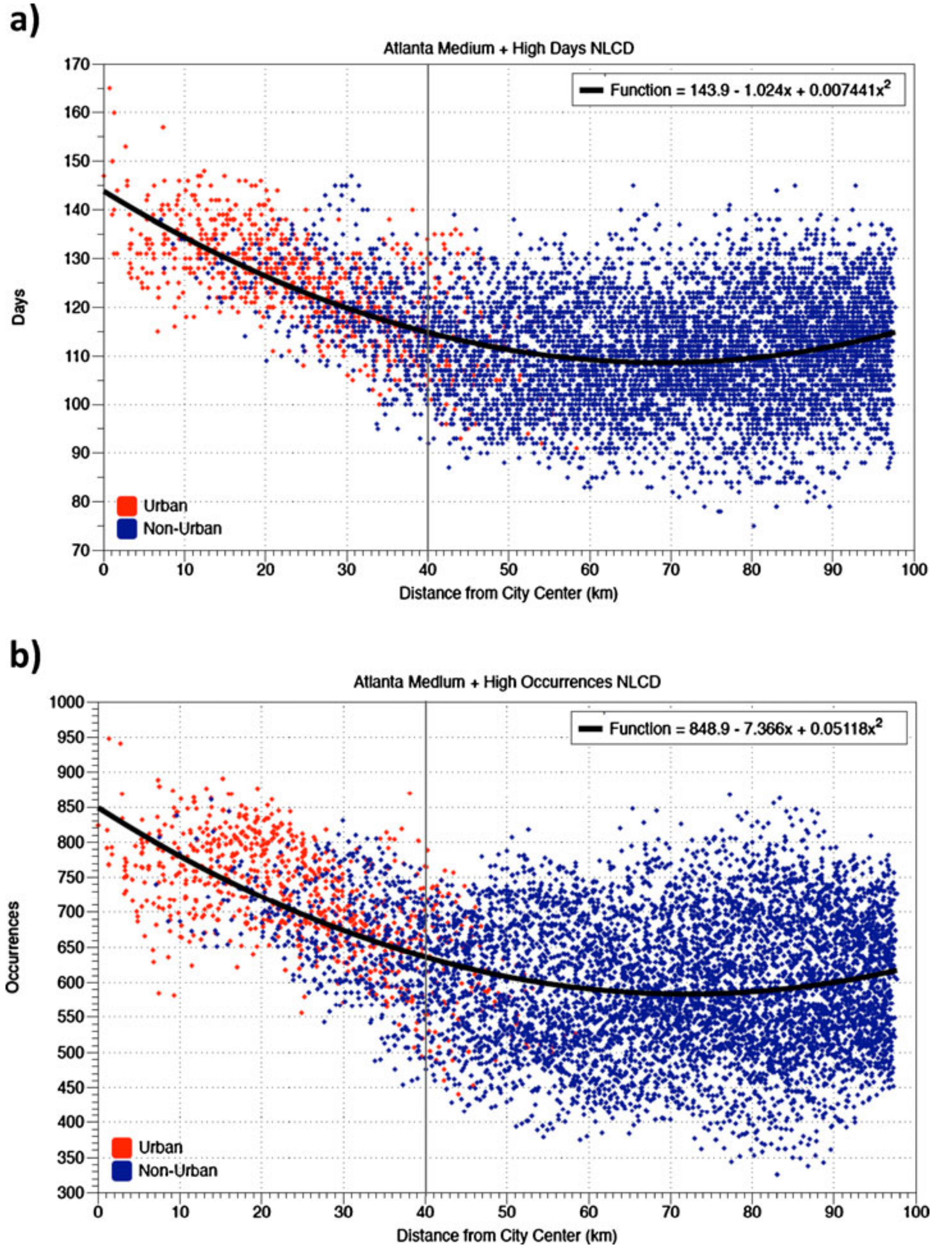

Fig. 3 Quadratic line fits and associated scatterplots representing the frequency of (**a**) total days ≥40 dBZ and (**b**) total number of 5-minute occurrences ≥40 dBZ for each 2-km grid cell versus distance from city center in the Atlanta domain for the 10-year, June–August period of record. NLCD urban delineated cells are colored red, whereas non-urban cells are blue. The 40-km urban buffer for Atlanta is represented as solid line emanating from the x axis

positive augmentations) were associated with high-end occurrences and days, suggesting that these urban areas are not only leading to an increase in thunderstorm frequency, but elevated occurrences of intense thunderstorm events.

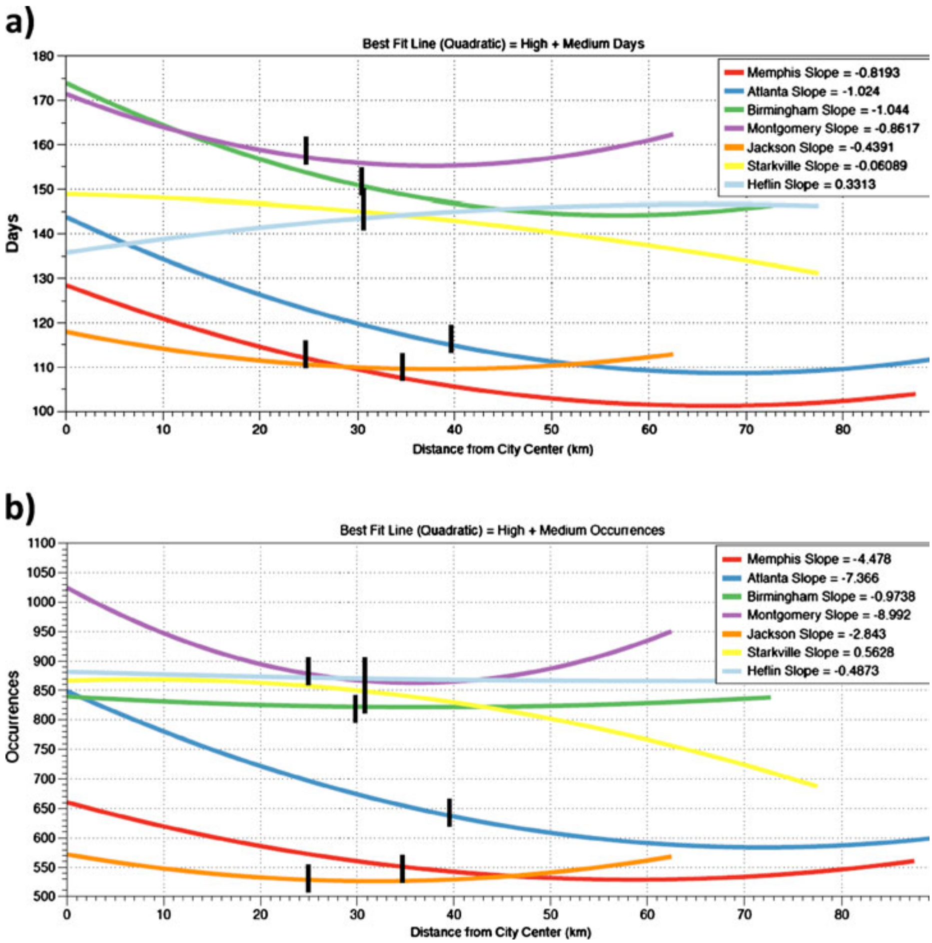

Fig. 4 Quadratic line fits representing the relative frequency of (**a**) total days ≥40 dBZ and (**b**) total number of 5-minute occurrences ≥40 dBZ versus distance from city center for the seven domains examined. Various urban-rural buffers used (see Table 1) are represented by black line segments

Birmingham demonstrates similar percentage increases, with high-reflectivity occurrences and days ranging from 11–70% increases in the urban versus rural regions. As discussed prior, the medium occurrences for Birmingham are conflicting, suggesting negligible change. Whether this is simply a reflection of the enhancement of moderate thunderstorm activity due to Gulf of Mexico proximity (Changnon 1988), or some other effect due to LULC-induced mesoscale circulations (e.g., effects of nearby Mitchell and Lay Lakes and associated lake breezes; Segal et al. 1997) is difficult to discern. Summing medium and high reflectivity days suggests that Birmingham experiences 7–19% more thunderstorm days in comparison to its rural surroundings; this is comparable to the urban domain percentage increases found in Atlanta (11–17%) and Memphis (11–24%) for total days.

Jackson experiences minor percentage changes from urban to rural; whereas, Montgomery features neutral to positive change, with high days and occurrences having the greatest differences (~16% positive augmentation). The null cases of Starkville and Heflin have conflicting results, with Heflin experiencing negative to neutral thunderstorm

Table 4 Percentage change in the mean frequency of reflectivity characteristics examined for different various urban delineation methods. Percentage changes in lightning counts and days are represented for Atlanta

City (urban delineation)	Reflectivity						Lightning	
	Medium Occurrences	High Occurrences	Total Occurrences	Medium Days	High Days	Total Days	Flash Counts	Flash Days
Atlanta (NLCD)	17.7%	42.9%	18.6%	9.0%	36.4%	11.7%	37.7%	19.5%
Atlanta (USGS)	23.7%	61.9%	25.0%	14.0%	54.5%	17.0%	41.7%	18.1%
Atlanta (Buffer)	16.7%	50.0%	17.8%	8.0%	36.4%	10.8%	34.2%	13.6%
Memphis (NLCD)	25.0%	47.1%	25.9%	20.2%	55.6%	23.3%	–	–
Memphis (USGS)	20.7%	47.1%	21.5%	22.3%	40.0%	24.0%	–	–
Memphis (Buffer)	7.5%	43.8%	8.6%	8.6%	33.3%	10.7%	–	–
Birmingham (NLCD)	3.3%	55.9%	5.5%	11.6%	33.3%	14.3%	–	–
Birmingham (USGS)	7.0%	70.6%	9.6%	15.5%	44.4%	19.0%	–	–
Birmingham (Buffer)	−1.5%	20.6%	−0.6%	6.3%	11.1%	7.5%	–	–
Jackson (Buffer)	−0.6%	0.0%	−0.6%	2.0%	0.0%	0.9%	–	–
Montgomery (Buffer)	2.6%	16.7%	3.1%	0.7%	15.8%	2.5%	–	–
Starkville (Buffer)	11.1%	32.0%	11.8%	4.0%	28.6%	6.5%	–	–
Heflin (Buffer)	0.8%	−17.2%	0.5%	−1.5%	−12.5%	−2.7%	–	–

percentages changes across the surrogate urban center and Starkville experiencing net percentage increases across the urban proxy. The mid size city and control city results are expected considering the prior conclusions drawn from the spatial and statistical perspectives.

Previous research has established that warm-seasonal rainfall increases of 5–25% over “background values” can be expected over and downwind of major urban areas that experience MT air masses (Huff and Changnon 1973; Changnon et al. 1981, 1991; Shepherd 2005; Burian and Shepherd 2005; Kishtawal et al. 2010). While these studies found increases in precipitation, they did not assess specifically the frequency of thunderstorm events or days employing high-resolution radar. Nevertheless, the percentage increases in thunderstorms over and near Atlanta, Memphis, and Birmingham suggested from our results compare well to the percentage increases found in the precipitation tallies of these prior works. This lends confidence to and reconfirms the hypothesis that large cities are enhancing not only precipitation totals, but thunderstorm formation, sustenance, and intensity.

Finally, examining 10 years of lightning data for the Atlanta domain supplements the strong evidence of urban modification of warm-season thunderstorm frequency and magnitude (Table 4). Using the three urban-delineation methods, the Atlanta urban area had a 34–42% increase in the mean lightning flashes per grid cell in comparison to the surrounding rural region. Lightning was, on average, 14–20% more common on any given day in the urban region versus rural region.

Because our observations were not stratified according to measured or inferred aerosol concentrations, it is difficult to disentangle how much aerosols contribute to our findings Indeed, land uses and aerosols are likely highly correlated, and their causal separation is best approached through an analytical framework other than the one deployed in this research. Nonetheless, despite a couple of decades of intensive research on urban weather anomalies, the relative importance of land cover versus aerosols, and how these two causal agents differ in their propensity to produce observational anomalies in radar reflectivities, cloud-to-ground lightning, and precipitation remains unclear.

4 Discussion and conclusion

Past research has demonstrated that large cities can augment sensible weather effects due to various urban-induced kinematic, thermodynamic, and pollution effects (Shepherd 2005; Shepherd et al. 2010). This prior body of work has focused principally on temperature and precipitation increases due to the aforementioned effects. Our study builds upon these efforts by presenting a high-resolution, radar-based climatology of warm-season convection for a multi-city region in the southeastern U.S., an area that has experienced considerable increases in urban and suburban populations over the last few decades. We characterized the frequency of moderate and high-end thunderstorms in an effort to see how cities reshape the distribution of convective hazards. Through this quantitative effort, we identified the scalar extents related to urban-enhanced convection. We implemented experimental controls, which has been cited as a major shortcoming in historical studies of urban-induced precipitation (Shepherd 2005).

Specifically, our results illustrate substantive evidence of urban effects on thunderstorm frequency and severity for major cities as well as evidence of non-urban LULC effects at a control site. The mid-sized cities of Jackson and Montgomery had more subtle urban effects, suggesting that urban impacts on convection are more muted and, therefore, the urban-enhanced dynamics are not significant enough to dominate other local/regional processes—i.e., the urban effects are embedded among larger controls. Therefore, the extent and shape of urban land cover can be seen as positively correlated with the potential for urban-augmented thunderstorms. Our explicitly geographic comparisons also illustrate how local city-specific interactions among urban land cover, topography, mesoscale circulations, and aerosol concentrations are superimposed upon this general trend.

As urban cities continue to grow into the 21st Century (UNFPA 2007), so will the convective feedbacks and, in return, enhanced thunderstorm risk they engender. When this risk is juxtaposed with elevated physical vulnerability created by urban infrastructure (e.g., impervious surfaces, outdated and aging storm drainage infrastructure, etc.), as well as the social vulnerability due to a concentration of millions of people and their assets into these centers (Borden et al. 2007), devastating consequences can result. The 2009-10 flooding episodes in Atlanta (Shepherd et al. 2011), Nashville, and Oklahoma City are illustrative of the disastrous consequences that can occur when heightened risk and vulnerability commingle at the scale of a metropolitan region.

Recently, the National Research Council (2010) highlighted three important weather research and transitional needs for the atmospheric sciences, with two of these needs—very high impact weather and urban meteorology—the focus of this specific work. The mixed-method analytical procedures employed within our study, while permitting the initial confirmation of patterns of thunderstorm augmentation by urban-rural heterogeneities, also provide a methodological foundation for future determination of other LULC and/or orographic effects on thunderstorm frequency. Forthcoming research employs the comprehensive radar database developed herein to investigate these additional effects as well as continue to analyze how humans, by way of their built environments, augment and modify local weather patterns and increase the risk of hazardous phenomena. This observationally driven, climatological research will continue to uncover the complex linkages, patterns, and processes, between humans, their environment, and the atmosphere.

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