CHARACTERISTICS OF URBAN LIGHTNING HAZARDS FOR ATLANTA, GEORGIA

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Abstract. Weather-related hazards are the result of interactions between the physical environment and the demographics of the community that experience them. Numerous studies have documented urban heat island (UHI) modification of cloud-to-ground lightning flash densities, but none have linked flashes to the underlying demographics. In this study, I compared flash and housing densities for 25 counties encompassing Atlanta, Georgia, using ordination and cartographic visualization. Over the interval 1992–2000, two densely populated suburban counties downwind from Atlanta (Gwinnett and Dekalb) exhibited the highest cloud-to-ground flash densities. By contrast, high population density counties located upwind (Cobb) and encircling the central city (Fulton) had relatively lower flash densities. Based on the interactions among demographics, flash density, and geographic position for a subset of counties, I outline four types of urban lightning hazards: emergent, UHI-augmented, UHI-suppressed, and non-interactive. For urban lightning hazards, the often invoked idea of 'more people equals more hazards' is to an extent simplistic. Urban areas have a large range of lightning hazards as heating nodes emerge, intensify, and shift in response to historically contingent patterns of growth.

1. Introduction

Lightning may outrank thunderstorm winds, heat waves, and droughts in the dollar amount of property damage in the United States, costing an estimated $332 million annually (Holle et al., 1996). Based on a summary of insured property loss claims, lightning losses for the state of Georgia were conservatively estimated at $18 million per year, far exceeding totals recorded in NOAA Storm Data reports (Stallins, 2002). Such lightning property losses can be attributed to background thunderstorm regime, a control imposed by the physical environment (Curran et al., 2000; Orville and Huffines, 1999). Lightning losses are also a function of the underlying demographic template, such as housing or population density (Changnon et al., 2000). Even though this concept of multiple causality in weather-related hazards is well-recognized (White and Hass, 1975; Mileti, 1999; Changnon and Changnon, 1998, 1999), surprisingly little has been articulated about its geographical detail. With lightning hazards, for example, changes in land cover may feed back to the local climate and alter thunderstorm regime. Subsequent modification of lighting distribution intersects with spatial patterns of land use to shape the distribution of lightning hazards.

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This developmental schema for lightning hazards was investigated within a multi-county region encompassing Atlanta, Georgia. Population in the greater Atlanta metropolitan area climbed from 2.9 million in 1990 to 4.1 million in 2000, a period of land use transformation unprecedented in the U.S. (U.S. Census, 2002). Recent investigations have documented the emergence of a strong urban heat island over Atlanta. Heat from downtown can modify local convective processes associated with thunderstorms (Quattrochi and Luvall, 1999; Bornstein and Lin, 2000). Urban lightning hazards have been identified by the U.S. Weather Research Program as an important area of research in consideration of the large economic liabilities embedded within urban regions (Dabbert et al., 2000). Of particular relevance are the potential additive lightning hazards that may emerge when urban heat island-modified cloud-to-ground (CG) flash densities are superimposed upon a heterogeneous landscape of population and housing densities.

To document the characteristics of urban lightning hazards, CG flash characteristics and demographic variables for 25 Atlanta area counties were analyzed using ordination and cartographic visualization for the interval 1992–2000. By mapping the distribution of lightning characteristics and their correspondence to demographic descriptors, more geographic detail can be acquired as to how lightning hazards emerge and shift in response to a complex causality. Given that this research seeks to develop a framework for more detailed hypothesis-driven analyses of the geographic patterns of urban lightning hazards, my techniques and observations were exploratory in nature.

2. Background

It has been long established that urbanization affects the thunderstorm climatology of cities and surrounding areas (Huff and Changnon, 1973; Changnon, 1981). Urban heat islands (UHI) may modify the formation and movement of convective storms (Bornstein and LeRoy, 1990; Bornstein and Lin, 2000). These studies have been clarified into a dual effect hypothesis. Surface-induced flow bifurcation around a city may lower the frequency of moving storms that pass directly over an urban area. Heat island-induced atmospheric convergence may also initiate new storms over or downwind of a city depending upon the strength of regional flows (Changnon, 1981; Bornstein and LeRoy, 1990; Changnon, 2001). Observational lightning studies have corroborated these urban influences on thunderstorm formation. Localized peaks in CG flash densities have been described for Houston (Steiger et al., 2002; Orville et al., 2001) and Bilbao, Spain (Areito et al., 2001). An enhancement of CG flash frequency on the order of 40–85% was observed for several large Midwestern cities (Dallas-Ft.Worth, St. Louis, Columbus, Louisville, Oklahoma City, and Omaha; Westcott, 1995).

Wescott's (1995) study of urban lighting is important in that it documents how densely built areas where heating effects are pronounced are not always the recipients of augmented flash densities. While calm regional flows may augment CG flash production directly over a city, flashes may also increase downwind relative to this heating center. Modeling by Baik et al. (2001) adds more detail to the dynamic patterning of urban lightning. As heating intensity increases, UHI-induced convection may move inward toward the heating center. With the emergence of multiple heating nodes as growth proceeds on the periphery of the central business district heating area (Stone and Rodgers, 2001), flash distributions may also shift. Consequently, observed flash densities in a densely-developed area should be viewed as a complex outcome of suppression and augmentation through downwind effects and local heating. It is important to note that the intent of this paper is not to prove the expression of one or another of these heating scenarios, but rather to fold them into the larger-scale patterns of flash density that emerge in Atlanta and hypothesize about their role in shaping the distribution of urban lightning hazards. In addition, I use the terms ‘suppression’ and ‘augmentation’ in reference to any relative difference in flash density between two locations. Delineating a ‘normal’ flash density from which decreases or increases are measured is problematic from the perspective of temporal scale.

Atlanta’s heat island has been thoroughly documented through Project ATLANTA (Atlanta Land-use Analysis: Temperature and Air-quality; Yang and Lo, 2002). Convective instability initiated by the Atlanta heat island has triggered local increases in the frequency of thunderstorms (Quattrochi and Luvall, 1999; Bornstein and Lin, 2000). However, the only studies to document flash densities for Atlanta were initiated as part of the weather safety planning for the 1996 Atlanta Olympics. Summertime (July–August) CG flash densities within 50 km of the city center were observed to average between 2.1–2.8 flashes/km^2/yr^{-1} with a few small peaks exceeding this range (Livingston et al., 1996; Watson and Holle, 1996). The interval over which these peaks were described, 1986–1993, did not exhibit noticeable UHI influences upon CG flash distributions. The time period assessed in this study, 1992–2000, coincided with rapid land use change and UHI intensification in the Atlanta region. This nine-year observational interval was comparable in duration to other urban lighting investigations. Longer temporal scales, while important for the documentation of upward or downward trends through time, do not necessarily improve the resolution of the spatial association between relative flash densities and demographics.

3. Methods

3.1. STUDY AREA

A 25-county area comprising 20,000 km^2 was selected for study, a geographic extent within the bounds employed in other urban lightning investigations (Areito et al., 2001; Wescott, 1995; Figure 1). Counties were designated as the observational unit given that public safety planning is often organized at this political level.

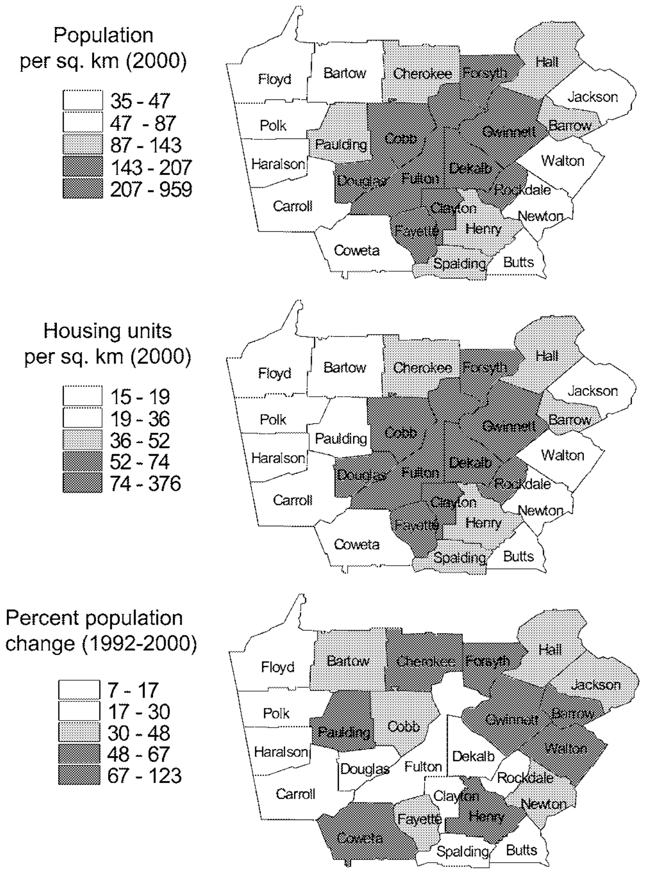

Figure 1. Demographics for the twenty-five county region encompassing Atlanta, Georgia (U.S. Census, 2000).

Counties range in size from 1370 km^2 (Fulton) to 339 km^2 (Rockdale). The highest population densities surround Fulton County, the location of the central business district. For 2000, Dekalb County ranked first in the state in population density (959 persons/km^2) followed by Cobb (690), Clayton (641), Fulton (596), and Gwinnett (525) (U.S. Census, 2002). Housing density followed a similar distribution, with the highest values in Dekalb County (376 units/km^2) followed by Cobb (270), Fulton (255), Clayton (234), and Gwinnett (187). Land use in Dekalb, Cobb, Clayton, and Gwinnett is predominantly suburban with commercial development increasing toward downtown Atlanta. Elevation ranges from 200–400 meters in the study area and is not a major influence on thunderstorm formation.

Population change over the interval 1990–2000 was greatest in the outlying counties of Paulding, Forsyth, and Henry. Henry County's population increased from 58,000 to more than 119,000 persons, an increase of 103%. Forsyth County, increased from 44,000 persons in 1990 to more than 98,000 persons in 2000, an increase of 123%. By comparison, the more densely populated counties of Dekalb and Fulton experienced a smaller percentage change in population. Steady growth in Gwinnett County occurred throughout the 1980s and 1990s. Paulding, Forsyth, Henry, Coweta, and Gwinnett ranked in the top ten fastest growing counties in the nation throughout the 1990s (U.S. Census, 2002).

3.2. ANALYSES

To document the relative distribution of flash density within the Atlanta region, binned county-level National Lightning Detection Network (NLDN) annual flash data (1992–2000) were imported into ArcView GIS software Version 3.2 (ESRI, 1998). Maps were constructed for mean flash density per square kilometer for the nine-year study interval and for each year. These annual maps facilitated identification of year-to-year flash density distributions that may have been obscured with a nine-year mean value. ArcView employs a natural breaks algorithm for objectively classifying data into interval classes. This widely-employed method of classification minimizes the variation among data values within classes and maximizes the variation between classes. Individual data values are reallocated from one class to another until the optimum classification is achieved. Natural breaks methods are more objective when compared to equal interval classifications, in which the cartographer chooses where to place the interval breaks in the data to map (Robinson et al., 1995; Campbell, 2001).

The most recent upgrade to the NLDN went into effect in 1995 (Cummins et al., 1998). This upgrade improved detection efficiency across North America from 65–80% to 80–90%. As the intent of this research was to establish the relative distribution of flash densities across the Atlanta area, lightning data were reported as observed. Changes in detection efficiency do not by logic negate any relative differences in flash density expressed within the Atlanta region for any single year. The upgrade also corresponded to the detection of a greater number of low peak current positive flashes. These flashes are hypothesized to be cloud-to-cloud flashes (Cummins et al., 1998) and have been estimated to contribute approximately 0.2 flashes/km^2/yr^{-1} to the total CG flash density over the study area. (Orville and Huffines, 2001).

Based on the findings of other urban lighting studies and the loci of UHI-initiated thunderstorm formation within the Atlanta region (Bornstein and Lin, 2001), higher flash densities were hypothesized to develop on the downwind (eastern and southern) side of the study area. Active summer thunderstorm days in Atlanta are supported by southwesterly flow in the lower and mid-levels, while cool season frontal thunderstorms track along a stronger, more west-northwesterly component (Livingston, 1996; Bornstein and Lin, 2000). It was also expected that downwind-upwind distributions of flash density relative to the Atlanta urban center were expected to become less apparent in later years as growing perimeter counties developed their own heat islands.

To characterize the covariance among demographic and lightning parameters, four county-level variables (cumulative percent change in the total number of flashes, cumulative percent change in flash density, percent change in population density, and percent change in housing density) were analyzed with principal components analysis (PCA). PCA can be used to extract and visualize the underlying covariance among variables in a data set (Manly, 1994). Though developed in disciplines outside of climatology, ordination methods such as PCA are commonly used in climate research (Easterling, 1999; Frei and Robinson, 1999).

PCA plots observations (in this case, counties) along perpendicular axes such that the maximum variance among their descriptors is projected on the first axis. The second and higher axes capture decreasing quantities of this variance. To enhance interpretation of how descriptors covary among observations, PCA axis scores can be correlated with the original variables. Spearman's correlation coefficients were calculated for PCA axis scores and county-level flash and demographic descriptors. Spearman's correlation coefficient (r_s) is a non-parametric rank order bivariate correlation statistic. The results of the PCA were then compared to the geographic location of counties and their absolute measures of flash and housing density in order to characterize the different categories of lightning hazards that develop within an urban region. PCA was performed in PC-Ord Software Version (McCune and Mefford, 1999).

4. Results

County-level maps suggested a tendency for higher densities to develop to the east of downtown Atlanta. This downwind cluster of high flash densities was more apparent in the years 1992 through 1997 (Figure 2). The highest mean annual flash densities were found in the dense suburban counties of Gwinnett (5.3 ± 1.6), Dekalb (5.0 ± 1.6), and in the more rural county of Newton (5.2 ± 1.6) (Figure 3). Not all densely developed counties were associated with augmented flash densities. High housing density was associated with lower flash densities in Fulton County (4.6 ± 1.1), the location of the downtown Atlanta, suggesting an urban heat island suppression of flash density over the central city. Densely suburbanized Cobb County (4.4 ± 1.0) in the western upwind sector of the city, and Clayton County (4.5 ± 1.5) to the south also had lower flash densities. Standard deviations for mean flash densities were larger than the potential contribution of low positive current cloud-to-cloud flashes. Maps with four and six classification levels produced similar results.

PCA summarized lightning and demographic descriptors (Figure 4) along two axes. Axis 1 captured 49.7% of the variance in the data set. The PCA axis scores for each county along the first axis had a strong significant positive correlation with housing density ($r_s = 0.9, p < 0.001$), and population density ($r_s = 0.9, p < 0.001$). As such, increasingly positive Axis 1 positions for counties

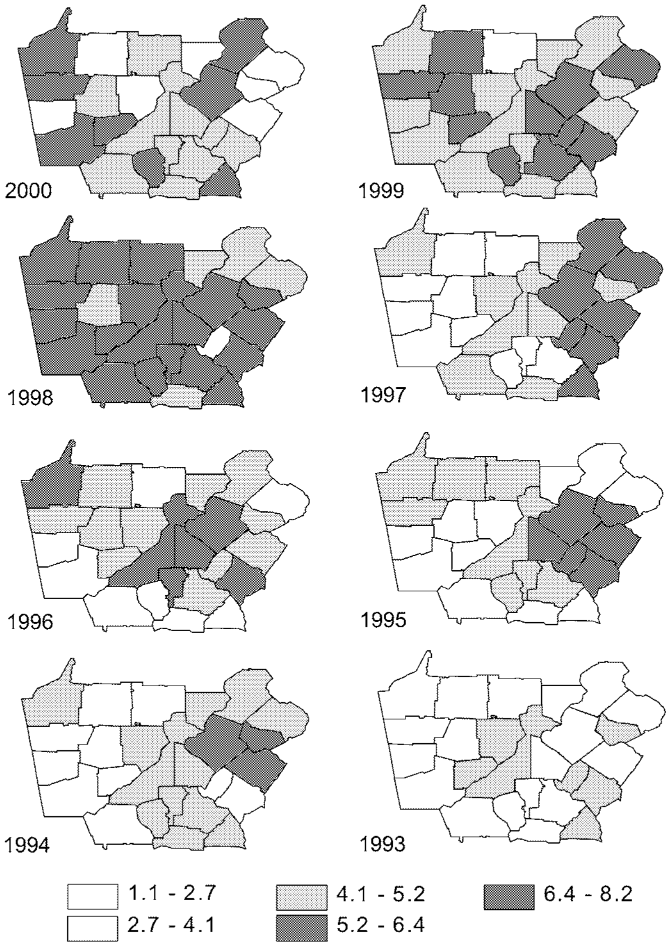

Figure 2. Year-to-year mean CG flash density per square km by county. 1992 was nearly identical to 1993 and is not shown. Mean annual flash densities for Cobb in 1995 (4.1) and Bartow in 1998 (6.4) corresponded to interval breaks. These counties were assigned to their lower interval.

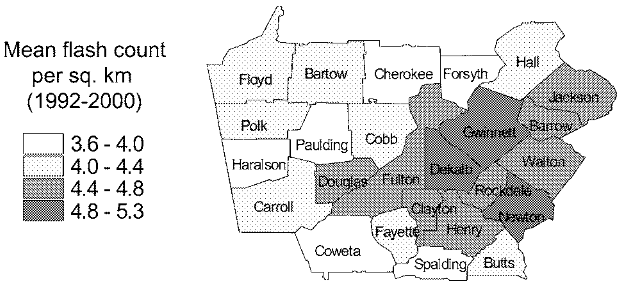

Figure 3. County mean flash density per square km for the interval 1992–2000. Mean flash densities for Forsyth (4.0), Fayette (4.4), and Barrow (4.8) corresponded to interval breaks. These counties were assigned to their lower interval.

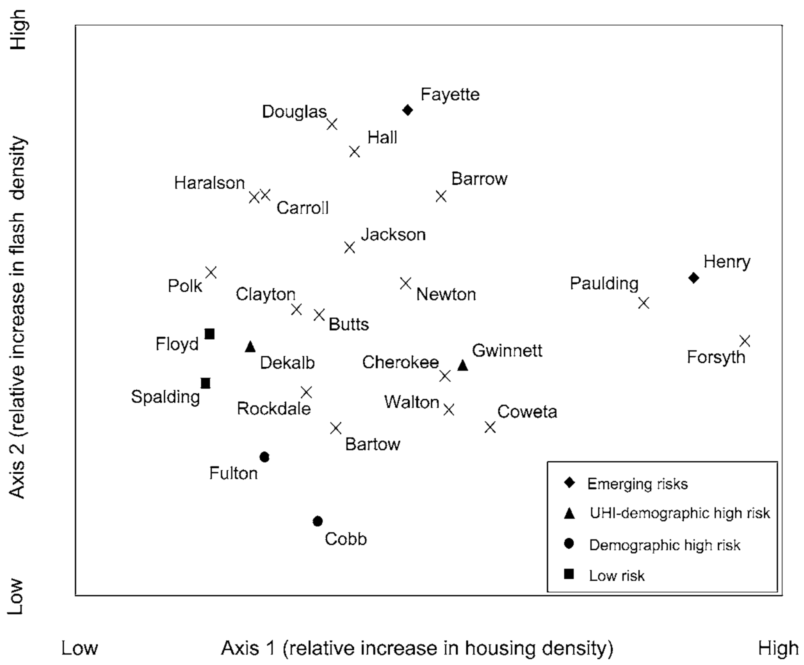

Figure 4. Scatterplot of PCA axis scores for individual counties. Counties positions along Axis 1 represent their relative increase in housing density. Counties positions along Axis 2 represent their relative increase in flash density. Distinctive lightning risk types are coded in legend, all other county axis scores denoted with an X. Axis scores in PCA are unitless.

indicate larger percentage increases in housing and/or population density. Axis 2 captured 27.5% of the variance. County positions along this axis had a significant positive correlation with annual cumulative percent change in flash density ($r_s = 0.8$, $p < 0.001$) and in the total number of flashes ($r_s = 0.7$, $p < 0.001$). In this case, the distribution of counties along the second axis represents their variability in lightning characteristics. Larger (more positive) axis 2 scores indicate greater percentage increases in flash density. As PCA expresses the maximum amount of variance along the first axis, the counties under study exhibited greater differences in demographics than flash characteristics. The third and higher axes did not have eigenvalues greater than one and are not reported (Legendre and Legendre, 1998).

To characterize urban lighting hazards, eight counties (Fayette, Henry, Dekalb, Gwinnett, Fulton, Cobb, Floyd, and Spalding) were selected as exhibiting large differences in their PCA axes positions, observed values for flash and housing density, and geographic position within the Atlanta region. Actual observed values for flash and housing density were included as part of the selection criteria since PCA assessed only percent changes for these descriptors. Only a subset of counties was selected so at to facilitate the parsimonious characterization of urban lighting hazard categories while avoiding any reification of the data under a more inclusive and formal classification of all the counties. From this group of eight counties, four general categories of urban lightning hazards were defined: emergent risks, UHI-augmented risks, UHI-suppressed risks, and non-interactive risks. They are described in more detail in the next section.

5. Discussion

Atlanta flash densities observed in this study were in general higher than those recorded by Livingston et al. (1996) during the summer months (June–August) of 1986–1992. This suggests that any persistent urban heat island-modification of lighting distribution may not have been fully developed at the time of their study, or more likely, the expression of higher flash densities may be more dependent upon the modification of fall and winter season frontal thunderstorms. The relative distribution of CG flash density among the counties in this study suggested a downwind enhancement, a pattern described for numerous other urban areas, including Houston (Orville et al., 2001; Steiger et al., 2002) and several cities in the U.S. Midwest (Wescott, 1995). Higher flash densities were observed for Dekalb, Gwinnett, and Newton counties. These counties were located in the downwind south and east corridors of the Atlanta region, thus decreasing the likelihood that higher elevations to the north of the study area were responsible for increased thunderstorm and lightning activity. Furthermore, these relative maxima in flash density in the downwind corridor were persistent for the years 1992 through 1997, suggesting that they were not an artifact of flash production during any single year.

The year-to-year maps also suggest that the distribution of flash density in Atlanta became less organized around a single downwind-upwind axis relative to the city center after 1997. One hypothesis is that the higher flash densities in eastern downwind counties were obscured after 1997 due to intensification of heating nodes in suburbanizing perimeter counties. The sprawl patterns of development that characterize much of suburban Gwinnett and Dekalb counties can contribute to surface heat island formation (Stone and Rodgers, 2001). In this scenario, flash density in Gwinnett County was initially influenced by its downwind position relative to the central city of Atlanta. As Gwinnett developed, its own heating may have begun to play a role in augmenting surrounding flash densities, thereby obscuring any large spatial scale upwind-downwind partitioning of flash density. Both Gwinnett and Dekalb counties may now serve as heat sources for other downwind locations in a manner similar to Fulton County during the early years of this study.

El Niño has the potential to enhance lighting production over the southeastern U.S. (Goodman et al., 2000). As an alternative hypothesis, the lack of organization in flash density magnitude around a large-scale downwind-upwind axis in 1998 may be a consequence of that year's strong late season (January–March) El Niño overriding local UHI influences. This event is a likely explanation for the uniformly high flash densities observed that year. Nonetheless, during the La Niña conditions of 1999 and 2000, when extrinsic forcings of thunderstorm formation and lightning

Table I
Urban lightning risk categories

Risk category	Relative property loss ranking	County	Cumulative percent change in flash density [a]	Percent change in housing density [a]	Housing density in units/km (2000)	Mean flash density (1992–2000)
Emerging risks	Increasing	Fayette	201	46	64	4.4 ± 1.9
		Henry	165	103	52	4.6 ± 1.7
UHI-augmented	Highest	Dekalb	140	22	376	5.0 ± 1.6
		Gwinnett	155	67	187	5.3 ± 1.6
UHI-suppressed	Potentially high	Fulton	120	26	255	4.6 ± 1.1
		Cobb	72	36	270	4.4 ± 1.0
Non-interactive	Low	Floyd	186	12	28	4.4 ± 1.6
		Spalding	133	7	45	3.8 ± 1.0

[a] One of four PCA variables.

production could be expected to decline, the upwind-downwind axis apparent in earlier years remains poorly expressed. More detailed spatial analyses are necessary to verify the extent to which the post-1997 changes in the scale expression of flash densities were the result of UHI influences.

Fayette, Henry, Dekalb, Gwinnett, Fulton, Cobb, Floyd, and Spalding counties were classified into four categories of urban lighting hazards based on their position in the PCA scatterplot, observed flash and housing densities, and location within the Atlanta region (Table I). Emergent risk counties had large percent changes in housing density, as indicated in the PCA axis 1 position for Henry County, or large percentage changes in flash density, as indicated in the PCA axis 2 position for Fayette County. Large percentage increases in housing or flash density (or both), rather than observed values for these parameters, suggest that the potential for lighting hazards may increase, particularly if the county is located downwind from a source of heating. Secondary downwind enhancement, originating from former perimeter counties that are now densely developed, may also contribute to augmented flash densities in this category of urban lightning hazards.

UHI-augmented risks, as exemplified by Gwinnett and Dekalb counties, arise from the coincidence of high housing densities and UHI-enhanced flash densities. For Dekalb, UHI-enhanced flashes were superimposed upon the highest housing density in the Atlanta region. This category can be assigned the highest level of risk given the potential for large property losses. While the high flash densities in this category may initially emerge from a position downwind from major heating centers, flash density could be later augmented by local heating effects.

Fulton and Cobb counties represent a category of urban lighting hazards in which high population densities correspond to lowered CG flashes. This may be due to a position upwind from heating centers (Cobb) or over the central city (Fulton). While any persistent high risks are moderated by the suppression of flashes, there still exists the potential for large property losses from a single lightning outbreak. For this reason, risk is potentially high in this category, with a strong dependence upon the flash characteristics of individual storms. Overall property losses in this category could be expected to be lower than areas designated as UHI-augmented.

The fourth category, designated as non-interactive, comprises low risk counties (Floyd and Spalding counties) that do not exhibit as strong an additive interaction among demographic and lightning trends. For these counties, building and flash densities are low. Percentage increases in demographic and flash densities are small and often inversely associated with each other.

6. Conclusion

Most of the recent population growth in Atlanta has been to the east-northeast of the city, an area downwind from the central heating center. Two counties in this quadrant, Gwinnett and Dekalb, merit designation as the highest risk counties in Atlanta because of the potential additive interaction between high housing densities and an urban heating-augmented flash density. Downwind effects and local heating are both likely to have contributed to the high flash densities observed for these counties over the study interval. While the county unit of observation facilitated the comparison of flash densities with census data, less spatially-constrained observational units and more intensive computational methods would increase the resolution at which urban lightning hazards can be identified.

Other variables may also influence the distribution of urban lightning hazards. While beyond the scope of this preliminary study, smaller spatial scale topographic and elevational contrasts, building type, and land cover (Pielke et al., 1997) should likewise influence lightning hazard patterns. Geographic variability in these descriptors, as well as the historical contingencies of demographics, suggests a large range in potential lightning hazards between and within urban regions. Standardized indicators drawn from insurance data and fire department response calls may be useful for validating city-to-city lighting hazard comparisons.

As a range of urban lightning hazard types were noted in this study, the often-invoked idea of ‘more people equals greater hazards’ overlooks some of the geographic nuance embedded in urban lightning hazards. For Atlanta, counties with high population densities were associated with suppression of flashes as well as downwind augmentation. For any single location in an urban region through time, its potential changes in flash densities are contingent upon the intensity and direction of land-use change and population growth. As growth proceeds in certain perimeter counties, and urban heating centers change in intensity, the location of UHI-enhanced flash densities should likewise shift and reorganize. Rather than drawing from static conceptualizations of risk, it may be productive to adopt this more developmental, geographic view of urban lightning hazards.

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