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Urban lightning climatology and GIS: An analytical framework from the case study of Atlanta, Georgia

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Abstract

There are three underdeveloped components of urban cloud-to-ground lightning studies: (1) the integration of multiple flash descriptors into more informative summary metrics of flash production, (2) the comparison of flash patterns by thunderstorm type, and (3) the correspondence of urban flashes with underlying land use. We used a GIS to integrate these components as part of an analysis of warm season (May–September) flashes for Atlanta, Georgia, a sprawling region in the thunderstorm-prone southeastern US. Our integrated metric of flash counts and flash days demarcated two large contiguous areas of high flash production in northeast Atlanta. Flashes which developed under conditions related to local surface heating and air mass instability more closely corresponded to urban land uses. Frontally-produced lightning was infrequent over the central city. Instead, peaks in production shifted to the periphery of the urban core, an observation suggestive of building barrier effects.

Keywords: Urban heat island; Land use; Lightning; Atlanta; Climate

Introduction

Urban areas alter the patterns of cloud-to-ground (CG) lightning. The first studies to suggest that cities have altered flash production tallied the number of days in which thunder or thunderstorm-related phenomena were observed. This methodology was used to document increased thunderstorm activity for Chicago (Changnon, 1968) and St. Louis

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(Changnon, 1978). More recent studies have mapped CG flash data obtained from ground-based lightning detection networks such as the National Lightning Detection Network (NLDN) in the US. Steiger, Orville, and Huffines (2002) used these data to describe patterns of flash production in the vicinity of Houston, Texas. Westcott (1995) used NLDN data to document enhanced flash production downwind of several North American cities in the midwest (Dallas-Ft. Worth, St. Louis, Columbus, Louisville, Oklahoma City, and Omaha). Urban flash studies have expanded to international locations as more detection lightning networks are installed (Areitio, Ezcurra, & Herrero, 2001; Naccarato, Pinto, & Pinto, 2003).

In this paper, we use GIS to document the warm season (May–September) patterns of urban flashes for Atlanta, Georgia over the interval 1992–2003. GIS applications in meteorology are increasingly frequent and offer new ways to combine and analyze weather data (Chapman & Thornes, 2003; Shipley, 2005). We employed GIS to map Atlanta's flashes so as to utilize three analytical methods that have not been extensively applied in urban lightning research. Each of these methods has the potential to improve how we visualize CG flash patterns and how we understand the mechanisms of urban lightning.

To analyze point data, some subdisciplines of physical geography have developed integrated metrics that combine density, frequency, and dominance. Forest biogeographers, for example, average relativized percent estimates for tree density (number of trees per unit area), dominance (basal area of a tree), and frequency (number of trees) to develop a measure of the importance of a particular tree species (Curtis & McIntosh, 1951). Lightning is an analogous point pattern phenomena that might benefit from an integration of multiple descriptors. Typically, flash maps present only one flash descriptor at a time. In this study, we combined the two most widely used flash metrics, density (or intensity of flashes) and flash day counts (or frequency of flashes).

Secondly, urban flash patterns can be assessed according to the synoptic setting under which thunderstorms develop. Thunderstorms generated along the less energetic, localized instability associated with air masses and thunderstorms generated along broader, synoptic-scale frontal boundaries produce different motions and thunderstorms dynamics. These thunderstorm types have the potential to influence urban flash patterns.

Thirdly, the patterns of urban flash patterns have been cast in rather generic terms (upwind, downwind, over the city center) and land-use, as a driving influence, has been descriptively generalized. Although it is recognized that urban areas have the propensity to alter patterns of CG lightning, few studies have coupled flashes and land use categories. This is critical since the extent flashes translate into hazards is in part dependent upon the underlying land-use type. For Atlanta, we examined how flash production coincided with two land-use classes: the high-density urban cover which is a source of urban heating, and the lower density urban land-uses where the suburban population resides. By making a more nuanced, GIS-based characterization of how flash production coincides with land-use, how it changes according to synoptic setting, and how integrated flash metrics can be applied, our investigation stresses a context dependency that has been only moderately developed in other urban flash hazard studies.

Background

Anthropogenic modification of thunderstorm activity in the vicinity of cities has a long and well-documented history (see review in Changnon, 2001). With the availability of data from the NLDN, it became possible to document urban modification of lightning production at resolutions and accuracies previously unattainable. Although satellite data is available through NASA's Global Hydrology and Climate Center, its resolution is larger (3–10 km), and there is no direct method for delineating cloud-to-cloud from CG flashes.

CG flashes recorded by the NLDN can result in large data sets, particularly when working in thunderstorm-prone regions. Approximately 8.2 million CG flashes were observed in Georgia for the twelve years of this study (1992–2003). For lightning climatologies, a large number of flashes, collected over many years, is needed to resolve lightning's high annual variability. Although it is increasingly easier to produce flash maps, mapping these long-term flash data sets over large areas has been a fairly time and labor intensive process. As a consequence, many of the first mapping projects were constrained to use a few standard visualization practices in which only a single descriptor was mapped.

GIS make it easier to integrate flash descriptors into a single metric of flash production. Flash production has been typically mapped in terms of its intensity, or flash density, defined as the number of flashes with a given area, typically a square kilometer. Frequency, the number of flash days per unit area, has also been employed. However, each of these two individual metrics communicates only part of the information needed to assess flash pattern and associated hazards. Flash density maps, for example, do not communicate information about the distribution of flashes among days when flashes occur. A high flash density may accrue over a few days during several large thunderstorms, or accrue incrementally from smaller thunderstorms over many days. Conversely, flash days do not communicate the concentration of flashes within any single day. High flash days may be observed for a location, but total flash density may be low or concentrated in a single day. To an extent, the mean number of flashes per day captures this association, but this value averages out potentially useful variability. By mapping the intersection of flash density and flash day counts simultaneously in a GIS, intensity and frequency metrics can be combined.

Another descriptor, dominance, is a measure of how flashes are distributed across an interval of time. For example, high flash counts for a location may be temporally distributed over a single year, a month, or concentrated in a single day. Dominance information can be expressed in a histogram or related graphical representations. Dominance can also be constrained in flash studies by the selection of a time period. Flash studies often limit the time window of their flashes according to some temporal criteria, such as warm-season months.

Flash data can also be combined with meteorological data. This facilitates the visualization of flash production patterns under different atmospheric condition and thunderstorm types. Previous studies suggest that urban flash patterns vary according to the conditions that initiate thunderstorms. Frontal thunderstorms may bifurcate around a city, an effect dubbed the building barrier effect (Bornstein & LeRoy, 1990). On days dominated by unstable maritime tropical air masses, urban heating may enhance convection within the city or at downwind locations (Bornstein & Lin, 2000; Dixon & Mote, 2003). As heating intensity increases, convection may move closer to the city center (Baik, Kim, & Chun, 2001; Changnon, 2001). By stratifying flashes according to whether the thunderstorm was initiated as a result of local surface heating and air mass instability, or as part of strong atmospheric instability associated with frontal boundaries, more details can be acquired about the geographic variability of urban flash patterns, as well as the robustness of any anthropogenic signal.

CG flashes can also be integrated with land-use data. Although the association of urban areas with increased lightning and thunder is longstanding, the spatial correspondence between flashes and urban land uses has been sparingly examined. Many of the maps used to infer surface cover types have been generalized, often using only an outline of the city boundaries. Flash distributions have also been generalized through contouring and smoothing algorithms. These generalizations are problematic not so much because flash patterns are coarsely represented on a map (indeed some level of flash generalization may be appropriate given the high year-to-year variability of flashes) but because areas of flash enhancement may erroneously be assumed to have a uniform level of impact on human systems when land uses are not defined.

Methods

Study area

We used integrated flash descriptors, flash data stratified by thunderstorm type, and land-use data to characterize flash production within an 80-km radius of a point originating from downtown Atlanta, Georgia (Fig. 1). This 80-km radius encompasses urban land uses towards its center and more rural areas in its periphery. Elevation increases from sea level on the Georgia coast up to 120 m in the Atlanta region. This state-wide elevational profile is not thought to play a direct and strong role in the upslope initiation of lightning in the Atlanta region. The 2004 population of the 10-county region surrounding Atlanta (Cherokee, Clayton, Cobb, Dekalb, Douglas, Fulton, Fayette, Gwinnett, Henry, and Rockdale) is 3.7 million (Atlanta Regional Commission, 2004). The city center is in Fulton County. Nodes of dense urban development are also found to the northeast in Gwinnett County, eastern Dekalb County, and to the northwest in Cobb County.

For the 80-km region surrounding Atlanta, 87% of its CG flashes occur from May to September. Early spring and late summer are characterized by more frontal flash activity associated with the passage of midlatitude cyclones. In summer, the instability to generate thunderstorms is often associated with weaker forcings from surface heating and unstable maritime tropical air masses. Although a large number of summer CG flashes occur in these weakly forced settings, eight of the ten highest flash count days in Georgia for 1992–2003 exhibited frontal boundaries and synoptic patterns that enhanced regional instability (Bentley & Stallins, 2005). The predominant thunderstorm-steering winds for Atlanta's latitude are found at 700-hPa. Average wind direction (May to September) for these mid-level winds is 273° (Shepherd, Pierce, & Negri, 2002).

Data and analyses

Flash data for the state of Georgia were obtained from the US NLDN (Vaisala, Inc.) for the years 1992–2003. Upgrades to the network in 1994 resulted in a CG flash detection efficiency of approximately 90% and a median location accuracy of 500 m (Cummins et al., 1998). Prior to 1995, CG flash detection efficiency was 70% with locational accuracy of 5–10 km. Flashes for 1992–1994 were mapped as recorded by the NLDN since it is not possible to derive the location of undetected flashes. The upgrade to the system resulted in the detection of low current, positive cloud-to-cloud flashes. As recommended by

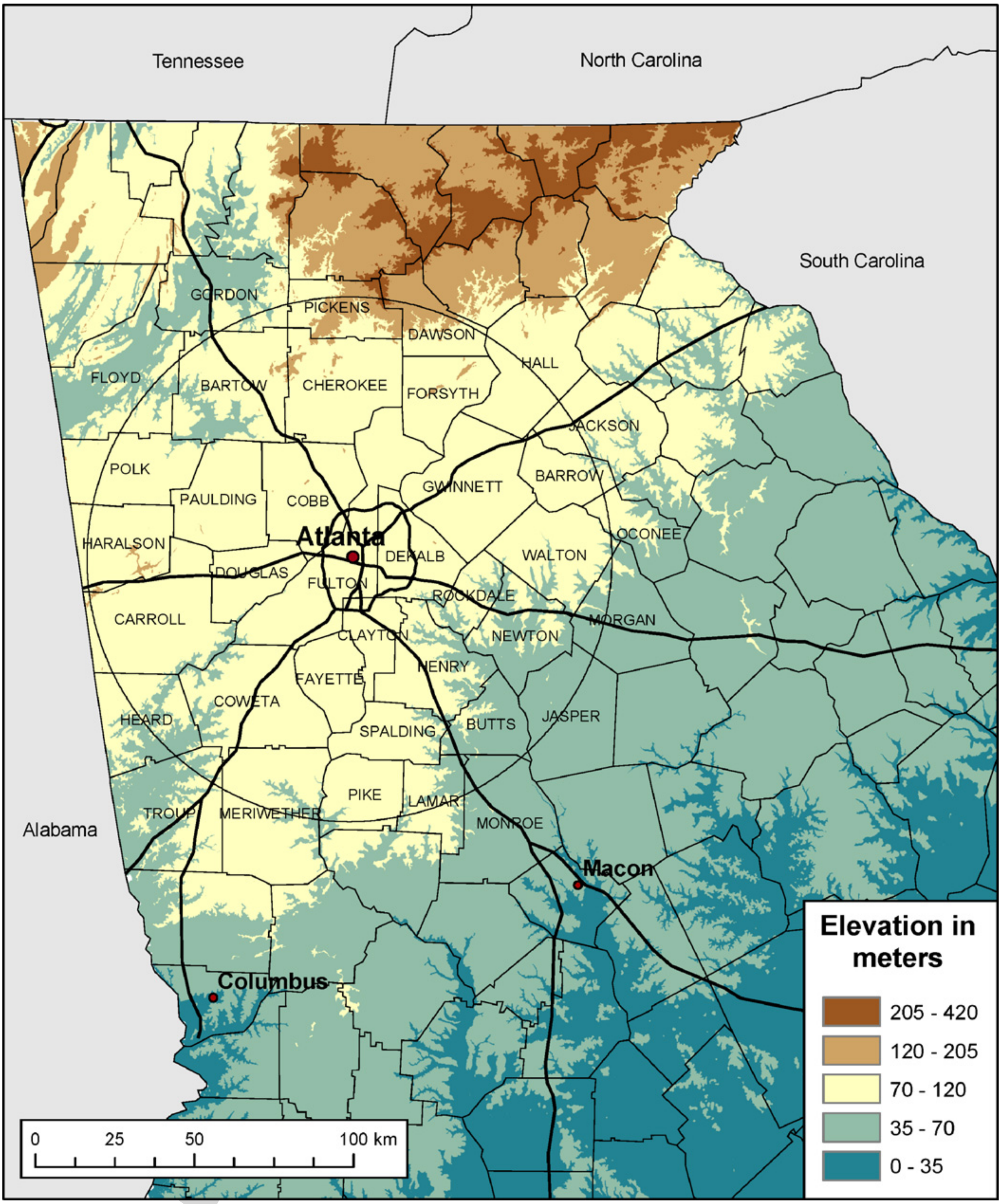


Fig. 1. Elevation and physiography of the north Georgia region (USA).

Cummins et al., positive flashes <10 ka were deleted from the dataset. Flash data were mapped in their native format in ArcGIS 9.0 (Environmental Systems Research Institute, 2004). No smoothing or estimator-based algorithms were used.

Flashes within 80 km of the central business district of Atlanta were reprojected to a Georgia statewide Lambert conformal conic projection and associated with 2×2 km grid cells. Rather than spatially joining flashes to this grid, we joined the grid to the flashes.

Table 1
Flash days and flash counts (positive and negative flashes) by synoptic category for the area within an 80 km radius of downtown Atlanta, May through September (1992–2003)

Synoptic setting for thunderstorms	Number of days	Total flashes
Air mass (weak forcing)	549	486,509
Frontal (strong forcing)	500	381,435
Indeterminant	66	67,018
Tropical	20	4134

This resulted in a unique grid cell location ID for each flash. By associating a specific grid location ID to each flash, we were able to query and summarize the flash data in Microsoft Access and then join these flashes to the study area grid via the grid cell IDs. This procedure decreased the time and computational effort needed to produce flash maps.

Map algebra functions were used to delineate high production areas based on a combined metric of flash density and flash frequency. First, flash density counts were relativized in each grid cell by dividing its observed flash count by the total number of flashes (939,096) within the 80-km study radius. A similar relativization approach was employed by Gauthier, Petersen, Carey, and Orville (2005). Flash days were relativized by dividing each cell's flash day count total by the number of days in which lightning was detected across the circular study area (1135 days). Then, grid cells for each relativized variable were expressed as a percentage and classified into four equal intervals. The upper two intervals from relativized measures of total flashes and flash day counts were selected and intersected into a single overlay. This distribution of flashes represents the grid cells experiencing a high number of flashes and a large number of days with flashes.

To compare flash patterns in a strong and weak thunderstorm-forcing environment, we first categorized the synoptic environment present during lightning days according to records in the Daily Weather Map Series. This database, produced by the National Oceanic and Atmospheric Administration, contains the 1200 UTC surface analysis for the United States. The approach developed by Dixon and Mote (2003) was used to assess the proximity of Georgia to frontal boundaries, extra-tropical low pressure systems and/or tropical systems for each lightning day in order to categorize the flashes as weakly forced or strongly forced, tropically forced, or indeterminate. Forcing attributed to indeterminant and tropical weather systems resulted in a very low number of flashes and were not examined further (Table 1).

To assess the spatial correspondence between land-use type and flashes, patterns of flash production were overlain upon a land-use classification of Landsat TM imagery for Georgia, from 1997 and 1998. Overall statewide accuracy of the land cover was 85%. Although the land-use classification has a resolution of 30 m, accuracy was not assessed on patches less than 4 pixels. Data are discussed in Payne et al. (2003).

Results

Three primary regions of high flash density were identified across the state: the Atlanta urban region, east-central Georgia, and along the Atlantic coast (Fig. 2). When flashes were mapped at the metro scale, defined as the area within the 80 km radius of the Atlanta

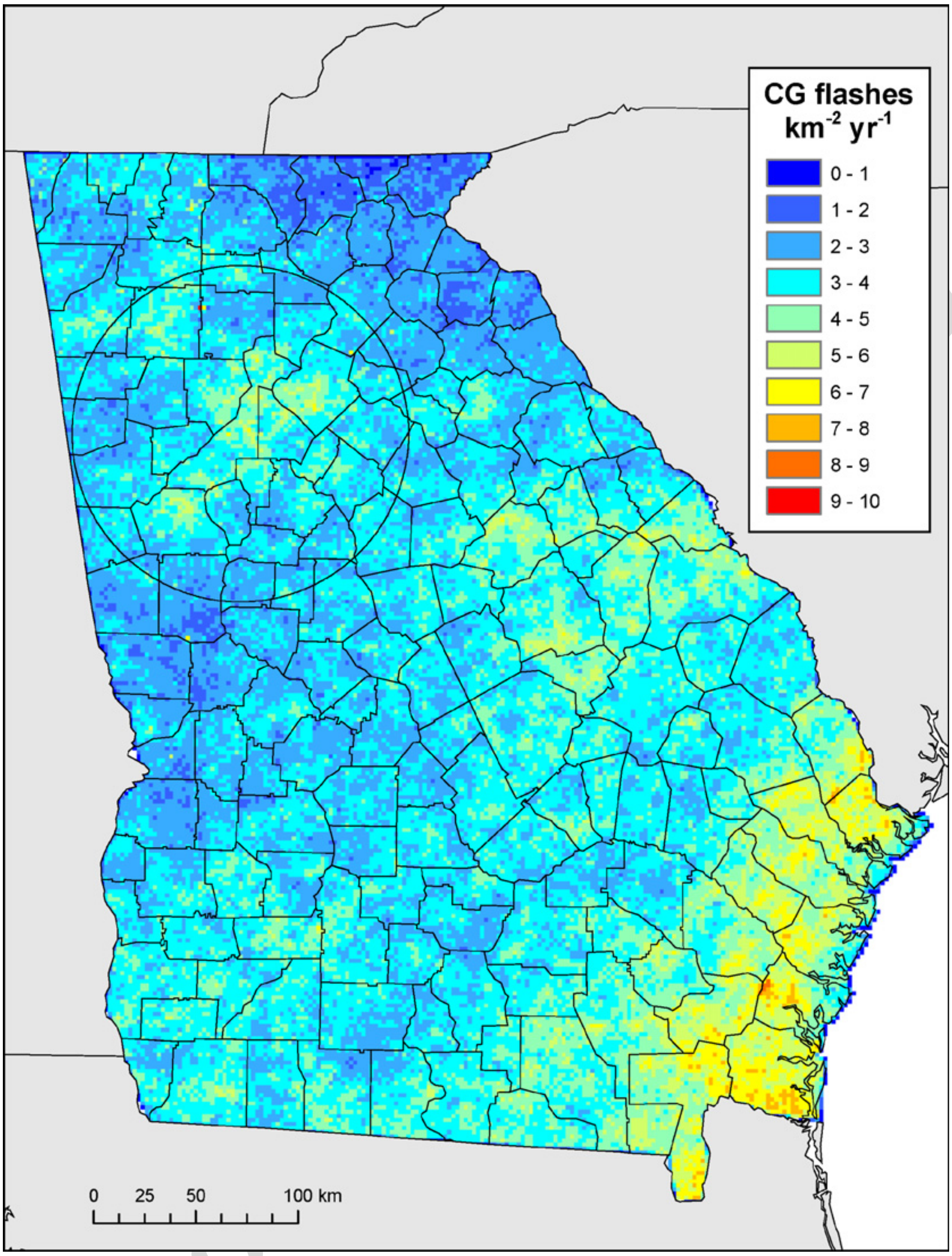


Fig. 2. State-level flash density. Because of the large size of the data set, we used neighborhood statistics, a kernel-based algorithm available in ArcGIS, to map density. Neighborhood statistics can be set to grid data by defining a search radius of 1 grid cell. Each grid cell is $2 \times 2\,km^2$.

city center, zones of high and low flash density within the Atlanta region became more distinct. Flash density peaked to the northeast of Atlanta in central Gwinnett County (7.6 flashes per square km; Fig. 3a). Flash day count peaks were more uniformly distributed over a wide swath of north–northeast Atlanta, ranging up to 116 days (Fig. 3b).

Relativized flash density percentage intervals were low given that there was a large number of flashes relative to the total number of flashes in each grid cell. The two highest percentage intervals of flashes (0.024–0.039%) aligned along a southwest-northeast axis across the city (Fig. 4a). The upper half of flash days (7.3–10.2%) were concentrated over the northeast corridor of Atlanta (Fig. 4b). The intersection of these two data layers

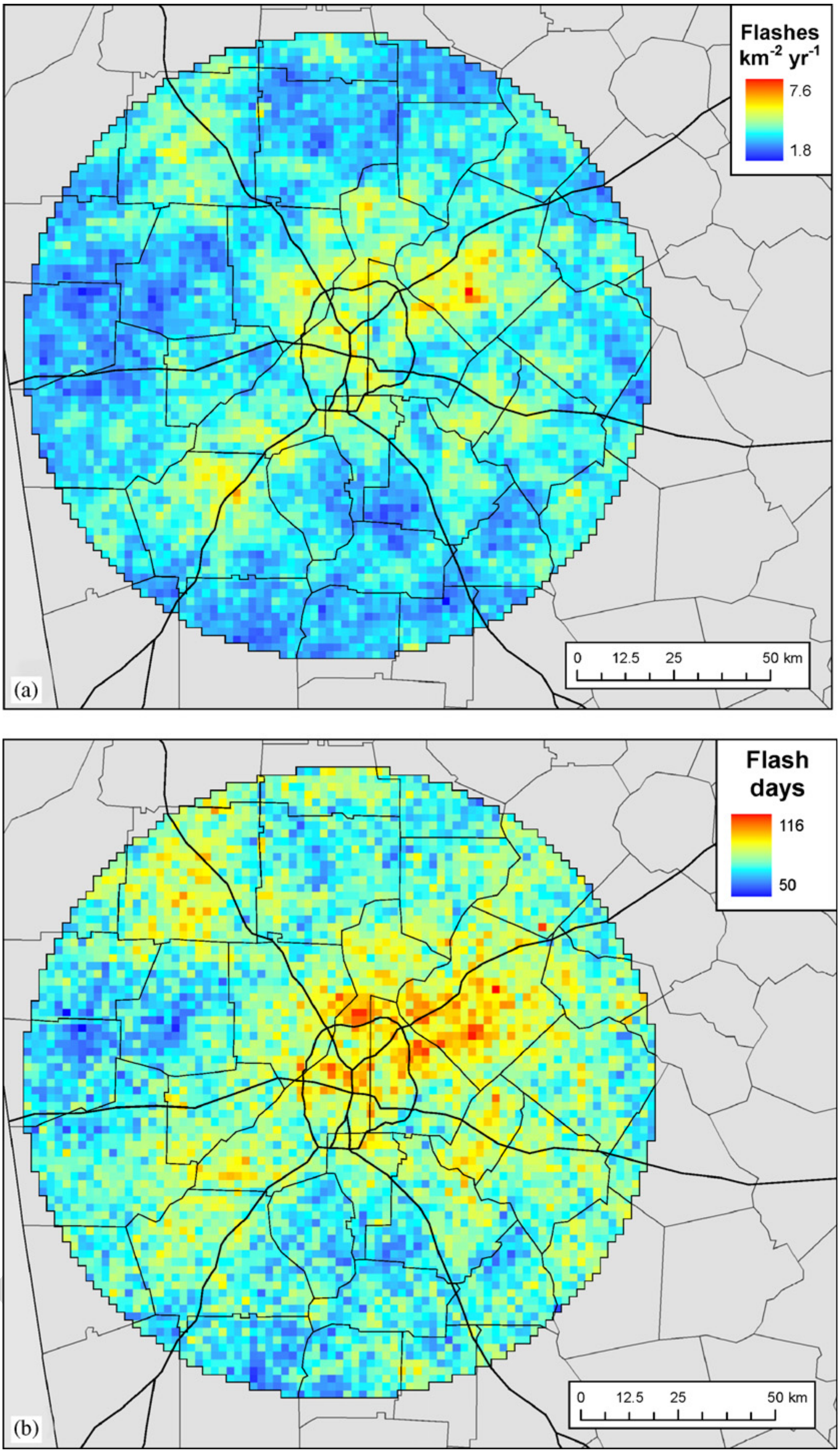
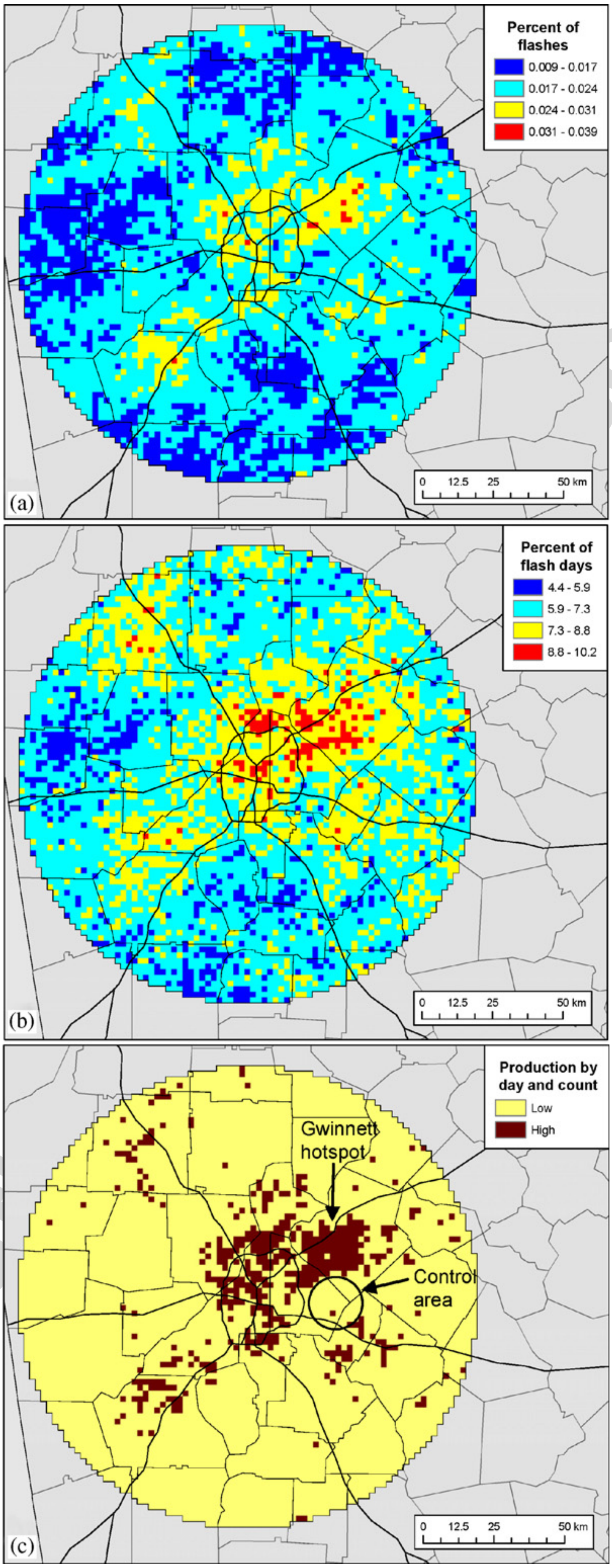


Fig. 3. Average annual flash density (a) and flash day count (b) for the 80-km region surrounding downtown Atlanta.


Percent of flashes
0.009 - 0.017
0.017 - 0.024
0.024 - 0.031
0.031 - 0.039
0 12.5 25 50 km
(a)
Percent of flash days
4.4 - 5.9
5.9 - 7.3
7.3 - 8.8
8.8 - 10.2
0 12.5 25 50 km
(b)
Production by day and count
Low
High
Gwinnett hotspot
Control area
0 12.5 25 50 km
(c)

demarcated 441 grid cells (1764 km^2) that had flash day counts and flash densities in the upper half of relativized values. After reclassification, two zones of high production, one in Gwinnett County (420 km^2) and in north-central Fulton County (160 km^2), became better defined (Fig. 4c).

To assess if this high production was temporally distinctive from the surrounding area, a subset of the flashes from a 300 km^2 area comprising the core of the Gwinnett County hotspot was selected and broken down into components of annual, monthly, daily, and hourly flash counts. Another 300 km^2 zone of flashes, immediately south, was selected as a control (Fig. 4c). Land use in this control zone was predominantly low-density urban, but flash production was in the lower half of relativized values. Both the Gwinnett flash zone and the adjacent control zone had late evening hour peaks in flash counts (9–11 pm LST; Fig. 5a). However, the number of flashes was consistently higher in Gwinnett. Annual trends had more year-to-year variability, but production remained higher in the Gwinnett flash zone (Fig. 5b). Only the years 1995, 1997, and 2003 had large differences, with production in Gwinnett nearly twice as high as the control. Monthly production peaked in late July for both locations (Fig. 6a and b). No one specific date dominated production for either zone, but Gwinnett had several larger flash events (Table 2).

Spatial patterns of flash production differed according to the synoptic conditions driving thunderstorm initiation (Figs. 7 and 8). Flash density on thunderstorm days with weaker forcing (initiated without enhancement from frontal boundaries) was focused more tightly around central Atlanta and within the developed corridors of Fulton and Gwinnett counties (Fig. 7a). Flash days for this thunderstorm type also exhibited a tendency toward clustering around central urban and northeastern suburban land uses (Fig. 8a). By contrast, frontal flash densities peaked around the north–northeastern arc of the city, and had a propensity toward lower values within the city center (Fig. 7b). Flash days associated with strong frontal forcings were more diffusely distributed across the region, with a tendency to align themselves only along a southwest–northeast axis (Fig. 8b). In part, this reflects the potentially larger geographic extent of frontal thunderstorms and their propensity to override local controls. No prominent central city flash activity was apparent for this thunderstorm type.

Flash production in the 300 km^2 Gwinnett County hotspot was concentrated in weakly forced thunderstorms, as fewer days in this category produced nearly the same number of flashes as the more frequent frontally forced storms (Table 3). The Gwinnett hotspot had nearly double the number of flash days than the adjacent control region under conditions of strong frontal support. When the number of flashes in each location were totaled in each synoptic category, more than twice as many flashes fell over the Gwinnett region despite their close proximity.

Our land-use image confirmed that there were three nodes of dense urban development in the Atlanta region (Fig. 9a and b). These nodes formed a Y-shaped pattern. Dense urban land uses extended from the central city to Hartsfield-Jackson Atlanta International Airport in the south, tracked along an interstate highway corridor in Gwinnett County to

Fig. 4. Relativized flash counts (a), and relativized flash day counts (b) expressed as a percentage and classified into four equal intervals. Flash production as based on the intersection of the two upper percentage intervals for relativized flash density and the number of flash days (c). The largest contiguous area of high production (designated as the Gwinnett County hotspot) was compared to the adjacent control area (approximate location designated by the circle).

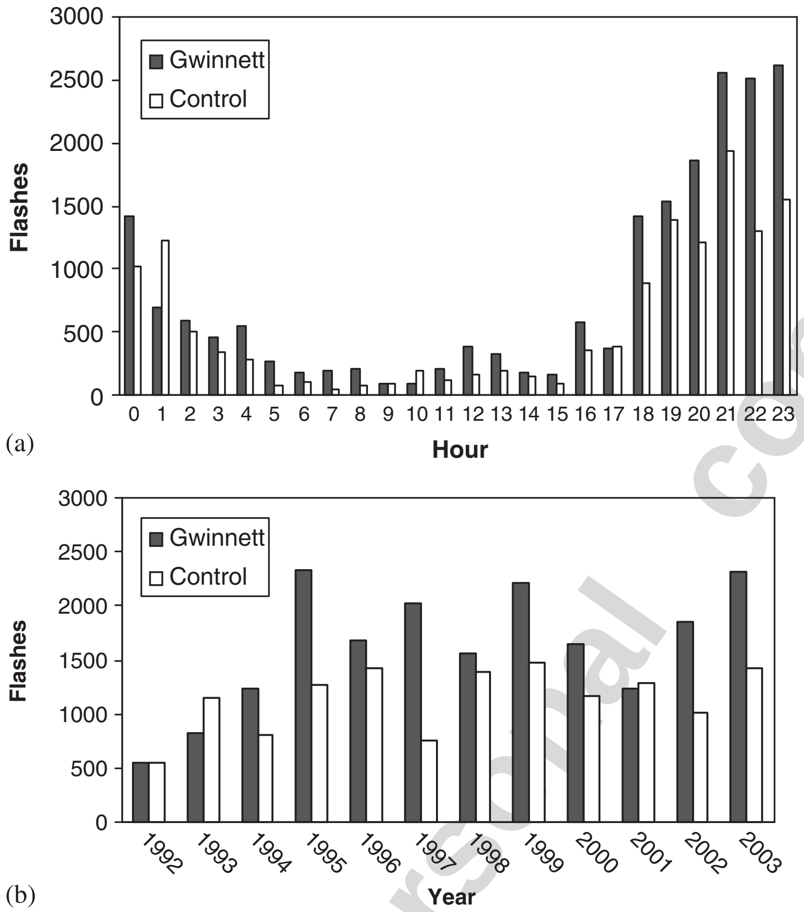


Fig. 5. Flash production counts by hour of the day (a) and year (b) for the Gwinnett County hotspot and the adjoining control region to the south.

the northeast, and developed in Cobb County to the northwest of the city. At the scale of the 80 km radius defining our study area, flash production generally increased as high and low density urban land-uses became more abundant. However, the occurrence of urban land uses did not necessarily imply the presence of high flash production. High density urban areas were not consistently associated with high flash production. Also, large tracks of low density urban cover in Cobb and Dekalb counties were disjunct from high flash production. Low density urban cover in Gwinnett County, by contrast, was associated with high flash production.

Discussion

A large contiguous areas of enhanced flash production occurs to the northeast of Atlanta. An adjacent area of lower flash production followed similar temporal trends, suggesting that urban effects are enhancing conditions for flash production when the broader-scale setting is already conducive for thunderstorm formation and lightning. A similar finding was reported in Stallins, Bentley, and Rose (2006). However, based on the findings in this study, we can partition these enhancement effects according to synoptic setting. Weakly forced air mass thunderstorms contribute to Atlanta's urban flash enhancement by increasing the number of flashes, while increases in the number of flash days is more a consequence of increased frontal triggering.

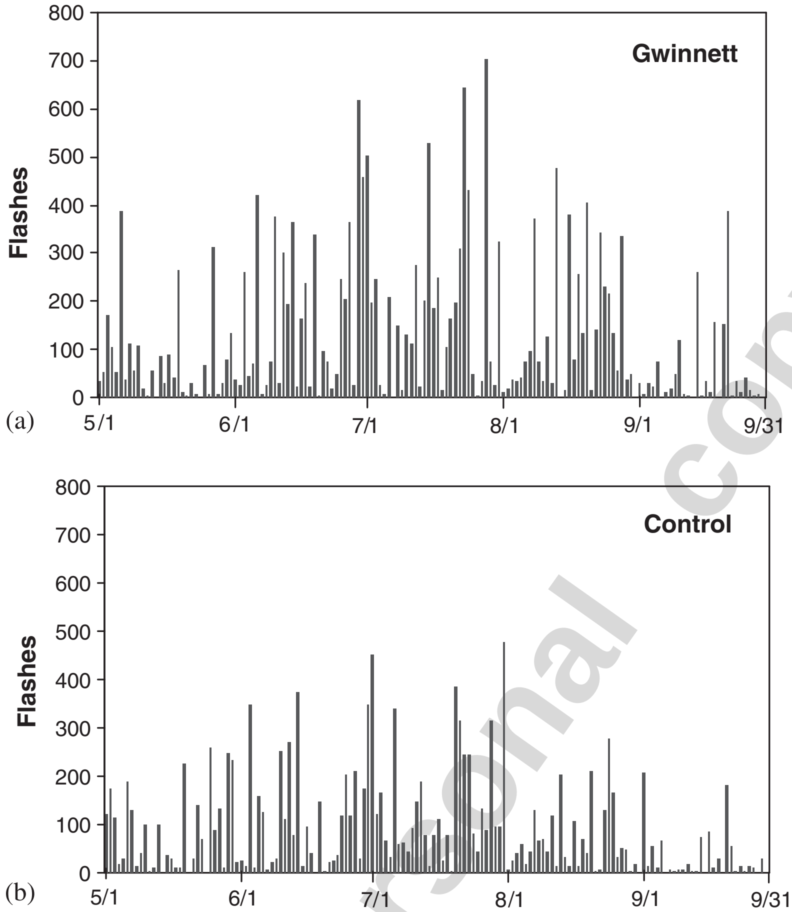


Fig. 6. Flash production counts by month and day for the Gwinnett County hotspot (a) and the control region (b).

Table 2
Ten highest flash production dates for zone of higher production in Gwinnett County and for adjacent area of reduced flash production to the south. Each area is 300 km^2

Location	Date	Number of flashes
Gwinnett zone	07/28/1997	585
	07/15/1997	468
	07/23/2002	426
	08/13/1999	379
	9/21/2000	348
	08/23/1996	339
	06/27/1994	337
	08/28/2003	335
	06/10/1995	327
	08/16/2003	297
Control zone	06/03/2001	306
	07/20/1998	291
	07/06/1999	274
	07/31/2002	257
	05/25/1996	254
	05/29/1998	234
	07/28/1993	234
	7/23/2000	211
	09/01/1995	203
	06/30/1999	193

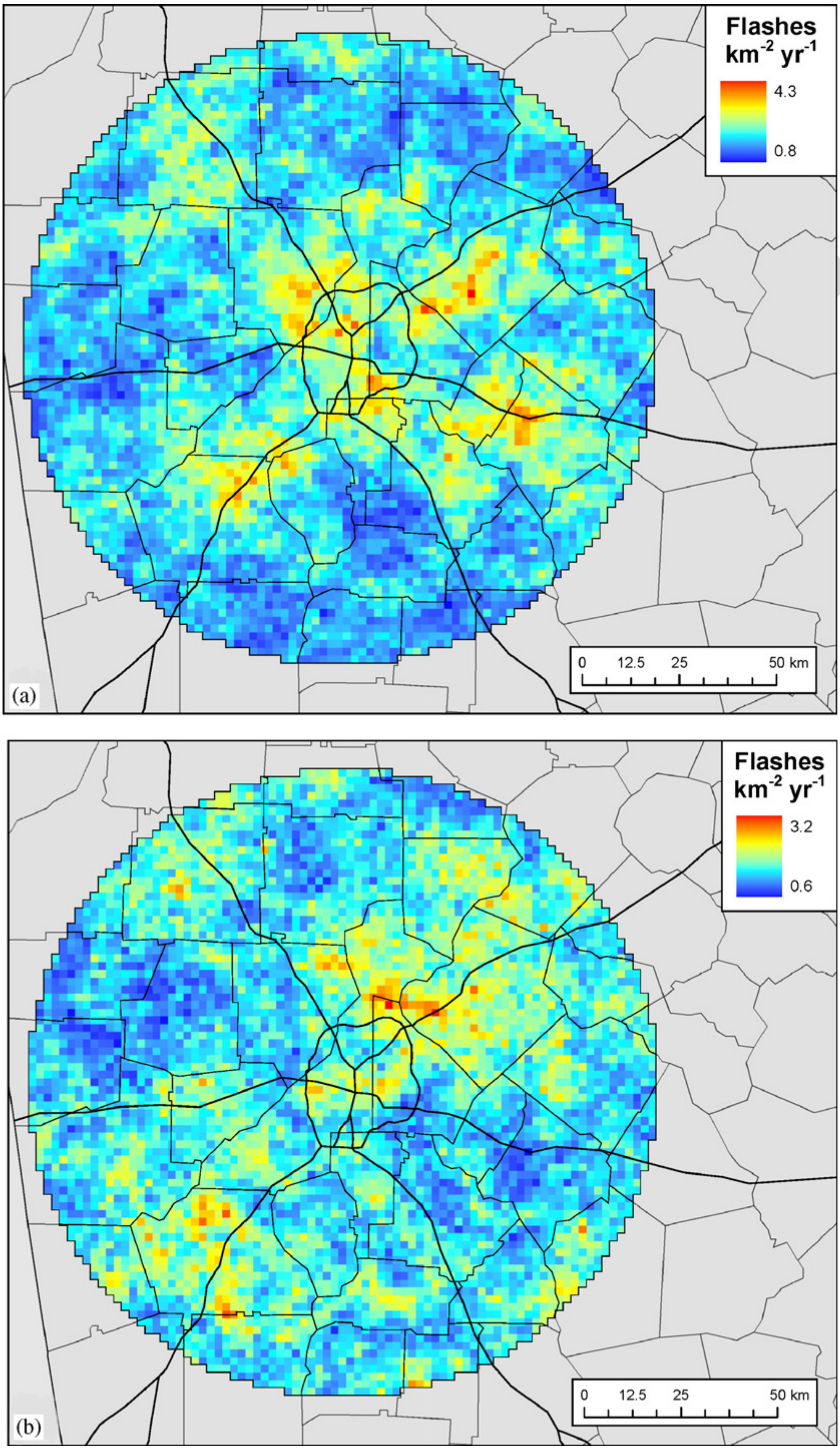


Fig. 7. Flash density for thunderstorms generated under a weakly forced setting (a) and for frontal thunderstorms with strong synoptic-scale support (b).

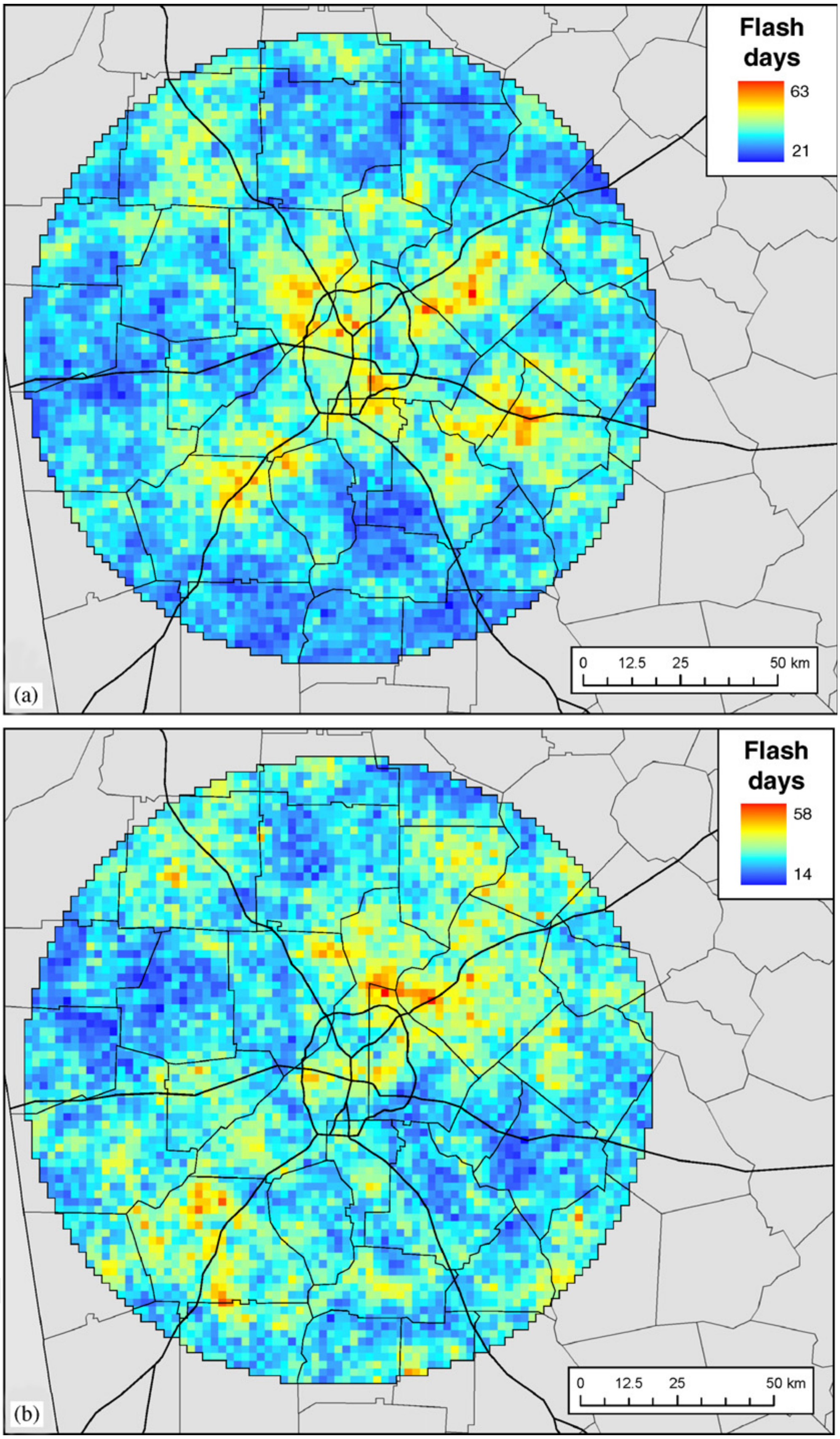


Fig. 8. Flash day counts for thunderstorms generated under a weakly forced setting (a) and for frontal thunderstorms with strong synoptic-scale support (b).

Table 3
Distribution of flashes and flash days in the Gwinnett hotspot and an adjacent control region. Flash density is measured in flashes per square kilometer

Synoptic conditions	Location	Days	Flashes	Flash density
Weak support (air mass)	Gwinnett	281	14,618	4.1
	Control	227	6,953	1.9
Strong support (frontal)	Gwinnett	381	12,716	3.5
	Control	212	5,261	1.5
Weak and strong support	Gwinnett	662	27,324	7.6
	Control	439	12214	3.4

Each area is 300 km^2. Density is expressed as average annual flashes per year per km^2.

Our integrated measure of relativized flash density and flash day frequency demarcated a modified corridor of high flash production when compared to maps for each individual descriptor. When the descriptors were integrated, a region of high flash density to the south of Atlanta in Coweeta County decreased in extent. At this location, flashes appear to have accumulated over a few days during severe thunderstorms that generated a large number of flashes. Our integrated measure of flash production was most useful for demarcating the contiguous region of high activity in Gwinnett County. The general outline of this hotspot was visible in the maps of each individual flash metric, but integrating them makes hotspot identification more objective. Nevertheless, flash metrics should not be integrated by default, as individual variables can also be meaningful. Even though flash density has been the standard measure used to demarcate urban flash enhancement, flash days may be more responsive to the different synoptic conditions under which thunderstorm and flashes develop. High variability in flash counts may mask the spatial correspondence between flashes and land use.

The spatial patterns of urban flash enhancement varied according to synoptic setting. On frontal days, there was a tendency for relatively lower flash densities and day counts to develop over the central city. This may arise from building barrier effects (Bornstein & LeRoy, 1990) that limit the incursion of frontal thunderstorms into the city center. Our observation of reduced flashes in the control area may be a consequence of its position in the shadow of building barrier effects triggered by the upwind Atlanta city center. Instead, high flash densities and high day counts from frontal thunderstorms emerged around the northeastern city perimeter. Air mass thunderstorms generated peaks in flash density and flash day counts within inner perimeter locations and within corridors to the northeast where suburbanization has taken place. Air mass flash counts and flash days more closely corresponded to locations that could be characterized as downwind of the Atlanta city center or as regions of heating in themselves. However, it is difficult to distinguish between downwind versus self-generating enhancement effects based on the exploratory methodologies in this paper.

Flashes increased as land uses became more urban. However, there was no clear association between flash production and urban land use. Such a finding could be expected given the spatial and temporal variability of thunderstorms and atmospheric processes in general. Nevertheless, when the underlying land uses and patterns of flashes are generalized or smoothed through cartographic techniques, the actual variability in the

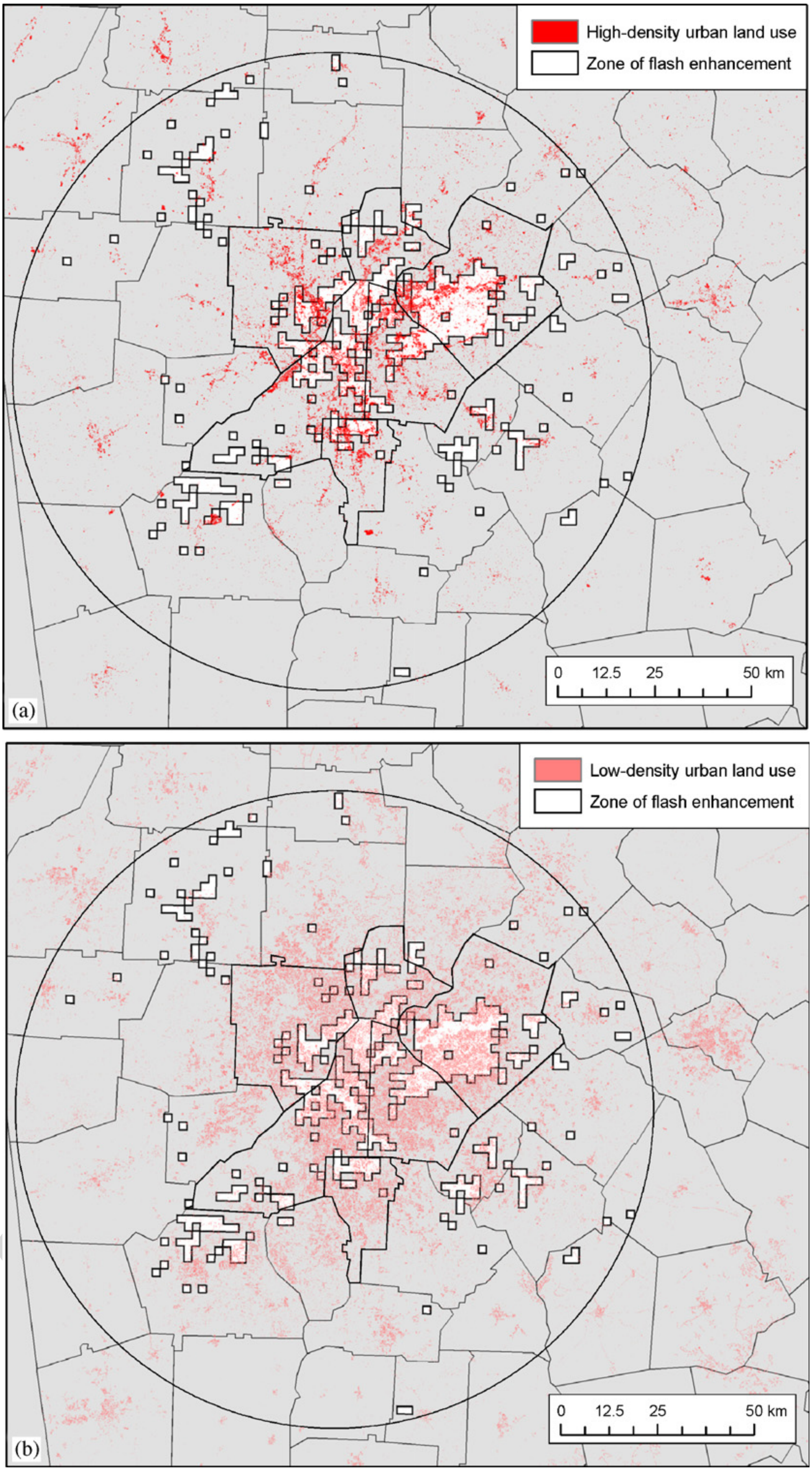


Fig. 9. Flash production and high-density urban land use (a), and flash production and low-density urban land use (b).

relationship between land use and flash production is not visible. This leads to a basically true statement, urban areas can have high flash densities, but one that is essentially incomplete and too overgeneralized to be of practical use. What may be more relevant for comprehending the covariation of land-use and flash production is the contingent distributions of land uses within Atlanta, and how they align relative to the city's upwind–downwind axis. Low density urban land use in northeast Atlanta are impacted by enhanced flash production through their own propensity to act as heating nodes and through their contingent position downwind from urban heating nodes.

Conclusion

GIS expands the methodological tools available to examine urban flash patterns. GIS simultaneously facilitates a disaggregation of flash data and a recombination of descriptors. It also provides a framework to integrate meteorological and land surface information. These practices may in turn provide more detail about the land-atmosphere processes contributing to urban flash enhancement. They also fashion a more locally based understanding of lightning hazards. CG flash hazards depend not only upon the size of a city, but also the contingent directions of growth and development, the orientation of heating nodes relative to wind direction, and thunderstorm type.

In Atlanta, zones to the north and to the northeast are coincident with high flash densities and high flash day counts. It could be expected that there are areas within the Gwinnett County hotspot in particular that have experienced high levels of property loss because of lightning strikes. Gwinnett County was one of the fastest growing counties in the nation throughout the 1980s and 1990s, and with it has come a densely built infrastructure and extensive suburban and urban development. Much of the recent increase in weather-related property hazards throughout the US can be attributed to conversions in land-use and subsequent increases in population where severe whether is common (Changnon, Pielke, Changnon, Sylves, & Pulwarty, 2000). Research is underway to establish if the Gwinnett County flash hotspots is disproportionately impacted by lightning property losses, and if local topographic features have any influence on the observed patterns of urban flashes.

Our research suggests that flash data that are smoothed, univariate, and examined without reference to the underlying land use may overgeneralize the risks associated with urban lightning hazards and lessen our theoretical understanding. Future work on urban convective processes and secondary phenomena such as lighting may benefit from approaches that map-specific storms and link them to anthropogenic and natural surface features. This process-based approach, when paired with visualizations of data aggregated and mapped over longer time scales, should reveal more detail about the patterns of urban lightning enhancement and the relative strength of any anthropogenic signal. Although we examined only one city in this study, comparisons among different cities would likewise aid in our understanding of how urban areas modify weather.

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References

Areitio, J., Ezcurra, A., & Herrero, I. (2001). Cloud-to-ground lightning characteristics in the Spanish Basque Country area during the period 1992–1996. *Journal of Atmospheric and Solar-Terrestrial Physics*, *63*(10), 1005–1015.

Atlanta Regional Commission (2004). *Population and housing 2004.* Available at http://www.atlantaregional.com/regionaldata/main.pdf.

Baik, J. J., Kim, Y. H., & Chun, H. Y. (2001). Dry and moist convection forced by an urban heat island. *Journal of Applied Meteorology*, *40*(8), 1462–1475.

Bentley, M., & Stallins, J. A. (2005). Descriptive climatology of cloud-to-ground lightning activity in the state of Georgia, 1992–2003. *International Journal of Climatology*, *25*, 1979–1996.

Bornstein, R., & LeRoy, M. (1990). Urban barrier effects on convective and frontal thunderstorms. Preprint volume, Fourth AMS Conference on Mesoscale Processes, Boulder, CO, 25–29 June.

Bornstein, R., & Lin, Q. L. (2000). Urban heat islands and summertime convective thunderstorms in Atlanta: Three case studies. *Atmospheric Environment*, *34*, 507–516.

Changnon, S. A. (1968). The LaPorte weather anomaly—Fact or fiction? *Bulletin of the American Meteorological Society*, *49*, 4–11.

Changnon, S. A. (1978). Urban effects on severe local storms at St. Louis. *Journal of Applied Meteorology*, *17*(5), 578–586.

Changnon, S. A. (2001). Assessment of historical thunderstorm data for urban effects: The Chicago case. *Climatic Change*, *49*, 161–169.

Changnon, S. A., Pielke, R. A., Changnon, D., Sylves, R. T., & Pulwarty, R. (2000). Human factors explain the increased losses from weather and climatic extremes. *Bulletin of the American Meteorological Society*, *81*(3), 437–442.

Chapman, L., & Thornes, J. E. (2003). The use of geographical information systems in climatology and meteorology. *Progress in Physical Geography*, *27*(3), 313–330.

Curtis, J. T., & McIntosh, R. P. (1951). An upland forest continuum in the prairie-forest border region of Wisconsin. *Ecology*, *32*(3), 476–498.

Cummins, K. L., Murphy, M. J., Bardo, E. A., Hiscox, W. L., Pyle, R. B., & Pifer, A. E. (1998). A combined TOA/MDF technology upgrade of the US National Lightning Detection Network. *Journal of Geophysical Research—Atmospheres*, *103*(D8), 9035–9044.

Dixon, P. G., & Mote, T. L. (2003). Patterns and causes of Atlanta's urban heat island-initiated precipitation. *Journal of Applied Meteorology*, *42*(9), 1273–1284.

Environmental Systems Research Institute. ArcGIS: Release 9.0 [software]. Redlands, California: Environmental Systems Research Institute, 1999–2004.

Gauthier, M. L., Petersen, W. A., Carey, L. D., & Orville, R. E. (2005). Dissecting the anomaly: A closer look at the documented urban enhancement in summer season ground flash densities in and around the Houston area. *Geophysical Research Letters*, *32*(10) Art. No. L10810.

Naccarato, K. P., Pinto, O., & Pinto, I. (2003). Evidence of thermal and aerosol effects on the cloud-to-ground lightning density and polarity over large urban areas of Southeastern Brazil. *Geophysical Research Letters*, *30*(13) Art. No. 1674.

Payne, K., Samples, K., Epstein, J., Ostrander, A., Lee, J. W., Schmidt, J. P., et al. (2003). Multisource data integration for Georgia land-cover mapping. *Southeastern Geographer*, *43*(1), 1–27.

Shepherd, J. M., Pierce, H., & Negri, A. J. (2002). Rainfall modification by major urban areas: Observations from spaceborne rain radar on the TRMM satellite. *Journal of Applied Meteorology*, *41*(7), 689–701.

Shipley, S. T. (2005). GIS applications in meteorology, or adventures in a parallel universe. *Bulletin of the American Meteorological Society*, *86*(2), 171–173.

Stallins, J. A., Bentley, M., & Rose, S. (2006). The extent of urban-modified cloud-to-ground flash characteristics (1992–2003) for Atlanta, Georgia (USA). *Climatic Research*, *30*(2), 99–112.

Steiger, S. M., Orville, R. E., & Huffines, G. (2002). Cloud-to-ground lightning characteristics over Houston, Texas: 1989–2000. *Journal of Geophysical Research*, *107*(D11) Art. No. 4117.

Westcott, N. E. (1995). Summertime cloud-to-ground lightning activity around major midwestern urban areas. *Journal of Applied Meteorology*, *34*(7), 1633–1642.