Weekend–weekday aerosols and geographic variability in cloud-to-ground lightning for the urban region of Atlanta, Georgia, USA

J. Anthony Stallins · James Carpenter · Mace L. Bentley · Walker S. Ashley · James A. Mulholland

Abstract We characterized the differences in warm-season weekday and weekend aerosol conditions and cloud-to-ground (CG) flashes (1995–2008) for an 80,000 square kilometer region around Atlanta, Georgia, a city of 5.5 million in the humid subtropics of the southeastern United States. An integration of distance-based multivariate techniques (hierarchical agglomerative clustering, multiresponse permutation procedures, fuzzy kappa statistics, and Mantel tests) indicated a greater concentration of CG flash activity within a 100 km radius around Atlanta under weekday aerosol concentrations. On weekends, these effects contracted toward the city. This minimized any weekly anthropogenic cycle over the more densely populated urban center even though this location had a higher flash density, a higher percentage of days with flashes, and stronger peak currents over the course of a week compared to the surrounding region. The sharper contrasts in weekday and weekend lightning regime developed outside the perimeter of the city over nonurban land uses. Here, lightning on weekend and weekdays differed more in its density, frequency, polarity, and peak current. Across the full extent of the study region, weekday peak currents were stronger and flash days more frequent, suggesting that weekly CG lightning signals have a regional component not tied to a single city source. We integrate these findings in a conceptual model that illustrates the dependency of weekly anthropogenic weather signals on spatial and temporal extent.

Keywords Climate change · Lightning · Aerosols · GIS · Bioclimatology

J. A. Stallins (✉)
Department of Geography, University of Kentucky,
1457 Patterson Office Tower, Lexington, KY 40506, USA
e-mail: ja.stallins@uky.edu

J. Carpenter
Graduate Program, Department of Atmospheric Sciences,
Colorado State University, 200 West Lake Street,
Fort Collins, CO 80523, USA

M. L. Bentley · W. S. Ashley
Department of Geography, Northern Illinois University,
Davis Hall, Room 118, DeKalb, IL 60115, USA

J. A. Mulholland
School of Civil and Environmental Engineering,
Georgia Institute of Technology, Mason Building,
790 Atlantic Drive, Atlanta, GA 30332, USA

Introduction

Humans modify weather and climate over a range of spatial and temporal scales. Among these anthropogenic effects is a propensity for convective weather phenomena to acquire a weekly signal. Most of the evidence for a weekly anthropogenic weather signal has come from rainfall studies at the scale of individual cities. Although some cities have weak to no detectable signals (DeLisi et al. 2001; Jin et al. 2005; Barmet et al. 2009; Bokwa 2010), others have been found to have wetter weekends (Marani 2010), drier weekends (Ho et al. 2009), wetter weekends with a seasonal bias (Simmonds and Keay 1997; Karar et al. 2006; Svoma and Balling 2009), and locally dynamic trends that differ in location and day of the week (Lacke et al. 2009). Weekday–weekend effects on rainfall have also been observed across broader spatial extents. Light rainfall events have decreased over northeastern China on weekends (Ho et al. 2009). Rainfall has a midweek peak over some areas of the United States (Bell et al. 2008; Tuttle and Carbone 2011) and on weekends over the

Atlantic adjacent to the US east coast (Cerveny and Balling 1998).

The range of these findings reflects how weekly signals are dependent upon geographic context. Arid versus humid climates, for example, have different weekly signals. But more importantly, the contrasts in these weekly rainfall studies raise the question as to how the areal extent analyzed constrains the identification of weekly trends and patterns in general. Geographers refer to this dependency as one of the components of the modifiable areal unit problem (Dark and Bram 2007). Hypotheses about the presence or absence of weekly signals confined strictly to an urban area may overlook their more heterogeneous distribution over the surface and the nature of processes that can explain them (Bell et al. 2008; Tuttle and Carbone 2011).

Compared to rainfall, lightning has been understudied for the expression of weekday–weekend effects. Although cloud-to-ground (CG) lightning detection network coverage did not become widely accessible until the mid- to late 1980s (Orville 2008), the number of weekday–weekend lightning studies is far less. Bell et al. (2009a) conducted the first significant mapping of weekend–weekday influences on cloud-to-ground (CG) lightning. They documented a weekly signal in cloud-to-ground (CG) lightning across the conterminous United States. However, its geographic expression was more complex. Although production peaked midweek when the data were aggregated, when mapped across the surface according to the day of the week, the signal became more heterogeneously expressed. Midweek peaks were present, but better developed in the eastern versus the western United States. But more surprisingly, urban areas were not associated with these peaks. Even though the aerosol air pollution and thermodynamic setting of cities are the causal drivers of their anthropogenic weather, locations outside of them were where weekday production was the greatest.

In this article, we characterize the geographic variability in the weekly cycle of CG lightning for the region surrounding Atlanta, Georgia. Compared to Bell et al. (2009a, b), we identify more of the regional detail as to how weekly signals are associated with urban cores. We quantify how production varies across a gradient or urban, suburban, and rural land uses. We also present a conceptual model to convey how weekly signals could vary in the vicinity of an urban region. Our goal is not to isolate a peak for a particular day of the week for Atlanta. We seek to identify the spatial heterogeneity of lighting production between weekday and weekend-like conditions across the entire region.

The idea that weekly cycles of weather have a distinctive geography has been noted by other scholars. As several other weekday–weekend studies of rainfall have observed,

weekly weather cycles may have become more widely distributed and incorporated into atmospheric circulation at larger spatial extents (Andreae and Rosenfeld 2008; Bell et al. 2008, 2009a; Kim et al. 2010; Tuttle and Carbone 2011). For example, distinct weekly signals were detected well outside of German cities (Baumer and Vogel 2007a, b). Winter weekend weather differences were evident at rural weather stations in Spain (Sanchez-Lorenzo et al. 2008). Across Europe, weekly effects have different regional signatures (Laux and Kunstmann 2008). Certainly, the methodological choices and data type (satellite versus ground-based) are factors that constrain the detection and comparison of weekly signals (e.g., Schultz et al. 2007; Franssen et al. 2009; Sanchez-Lorenzo et al. 2009). However, what these studies illustrate is that the line of inquiry is expanding from whether or not there are weekend–weekday effects to how these effects are geographically variable.

Mechanisms

Thermodynamic (Rozoff et al. 2003; Han and Baik 2008; Shem and Shepherd 2009; Gauthier et al. 2010) and aerosol mechanisms (van Den Heever and Cotton 2007; Ntelekos et al. 2009; Levin and Cotton 2008) are invoked to explain how humans modify rainfall and lightning. Aerosols modify lightning production by altering the timing of convective motion in a thunderstorm (Orville et al. 2001; Rosenfeld et al. 2008; Saunders 2008). Relatively polluted continental aerosols slow the rate at which cloud droplets coalesce into larger diameter raindrops, thereby transporting more cloud water above the freezing level where it can form the frozen hydrometeors involved in the noninductive charge separation process leading to lightning. Release of latent heat upon freezing invigorates further convective development, the production of lightning, and prolongs thunderstorm duration. This microphysical process is invoked to account for differences in convective cloud structure, precipitation, and lightning production in urban versus nonurban contexts (Rosenfeld et al. 2008; Bell et al. 2009a).

In addition, the timing, strength, and duration of the updrafts and downdrafts also depend on aerosol concentration. Microphysical effects may be greater at low rather than high aerosol concentrations (van Den Heever and Cotton 2007; Storer et al. 2001).

Aerosol radiative effects may also evolve. As one example, insolation at the surface may decrease as aerosols increase in concentration. Cooling of the surface may then stabilize the lower atmosphere and decrease the capacity for the convection necessary for microphysical processes to develop (Koren et al. 2008; Altaratz et al. 2010). However,

thermodynamic mechanisms like urban surface roughness, moisture availability, wind shear, and sensible-latent heat flux may still be required to initiate the convection that permits these microphysical and radiative aerosol processes modify (Dixon and Mote 2003; van Den Heever and Cotton 2007; Khain et al. 2008; Farias et al. 2009; Fan et al. 2009; Shepherd et al. 2010; Niyogi et al. 2011). Although our subsequent results and discussion suggest that weekday–weekend lightning effects are aerosol driven, they do not preclude the coexistence of aerosol and thermodynamic mechanisms and feedbacks between them (Stevens and Feingold 2009). Our goal in this article is not to attempt to rank the importance of these two explanatory frameworks. We wish to characterize the geographic distribution of a weekly signal in CG flash production with the assumption that aerosol and thermodynamic mechanisms conjointly underlie them.

Increasing concentrations of urban aerosols have been correlated with greater total CG flash production (Westcott 1995; Orville et al. 2001; Steiger et al. 2002; Pinto et al. 2004), although topographic or synoptic setting can be a mitigating factor (Soriano and de Pablo 2002; Morales Rodriguez et al. 2010; Lal and Pawar 2009). Aerosol diameter is also correlated with flash polarity. Flashes can come in two polarities, negative or positive. Coarser urban aerosols lead to more CG flashes but with a decreasing percentage of +CG flashes (Orville et al. 2001; Steiger and Orville 2003; Naccarato et al. 2003; Kar et al. 2009; Farias et al. 2009). By contrast, fine aerosols associated with biomass burning and forest fires increase CG flash production and the percentage of +CG flashes (Lyons et al. 1998; Murray et al. 2000; Fernandes et al. 2006; Rosenfeld et al. 2007). Greater vertical transport and weaker downdrafts associated with smaller-diameter aerosols may redistribute hydrometeors so as to promote a reversed polarity structure capable of producing more positive flashes (Carey and Buffalo 2007; Rudlosky and Fuelberg 2010).

Because of the potential variability in the size and concentration of aerosols, in the feedbacks among microphysical and radiative mechanisms, and in the nonstationarity of weekly emissions signals, one should expect considerable heterogeneity in the patterns of CG flashes. Accordingly, our paper is not an explicit test of any single hypothesis about causal mechanisms, such as whether land cover or aerosols are more important. Instead, it adopts an exploratory, visualization-oriented approach to examine how weekday–weekend lightning production varies across a gradient of land uses with different aerosol regimes. Exploratory approaches allow more flexibility to consider multiple process-based interpretations of observed patterns. We employ our findings to conceptualize some of the geographical components inherent in the detection of weekly effects. We present a graphical model that

illustrates how contrasting findings about weekly effects may be compatible through consideration of scale. Although our results are descriptive, we rely upon multiple lines of converging visual and statistical evidence to support our interpretations.

Study region

Atlanta, Georgia (33°45′N 84°23′W), is situated in a humid subtropical climate and experiences frequent synoptic-scale frontal and locally forced thunderstorms. The Atlanta region (Fig. 1) underwent a rapid conversion of land uses in the last three decades of the twentieth century (Yang and Lo 2002). Although there have been improvements in recent years, high volumes of emissions from vehicular traffic as well as local point sources of industrial air pollution routinely place Atlanta among the most polluted cities in the United States. A decade of studies have corroborated Atlanta's propensity to alter convective phenomena (Bornstein and Lin 2000; Shepherd et al. 2002; Dixon and Mote 2003; Mote et al. 2007; Diem 2008; Shem
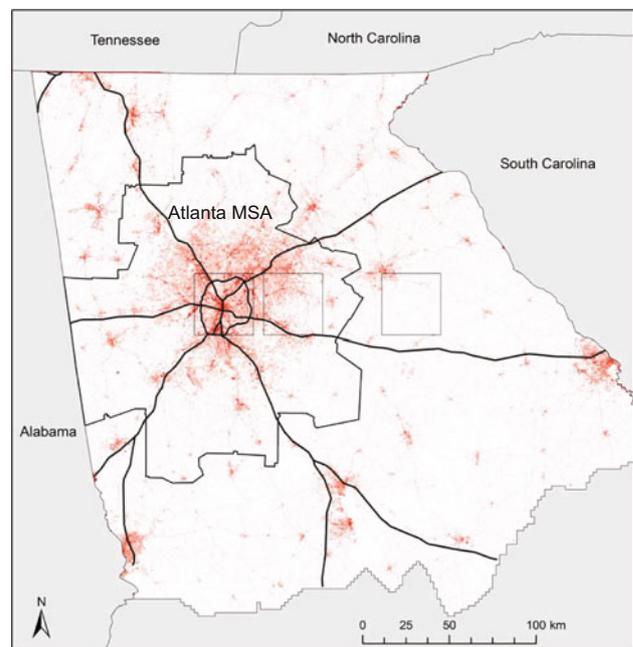

Fig. 1 The Atlanta study region. The irregularly shaped polygon around Atlanta is the boundary of the Atlanta Metropolitan Statistical Area (*MSA*). The 2009 population of the Atlanta MSA was approximately 5,500,000. *Shading* reflects the percentage of impervious cover (Natural Resources Spatial Analysis Laboratory 2005) with *darker shades* reflecting higher percentages. The wheel and spoke structure is the interstate highway system leading in and out of Atlanta. The *circle* in the middle is Atlanta's perimeter loop interstate, I-285. The *three rectangular boxes* demarcate areas where flashes were sampled for multivariate analysis

and Shepherd 2009; Lacke et al. 2009). CG flash densities increase around the city due to more days with lightning and greater lightning production when the region favors thunderstorm development (Stallins et al. 2006). Frontal thunderstorms tend to bifurcate around the city, while CG lightning from local air mass thunderstorms moves inward toward the city center (Stallins and Bentley 2006). Downwind flash augmentation can develop with a range of midlevel wind directions, not just the predominant westerly regime (Rose et al. 2008).

Weekly cycles of air pollution have been observed for the city of Atlanta (Wade 2005; Blanchard et al. 2008) as well as for larger regions of the United States in general (Murphy et al. 2008; Bell et al. 2009a; Rosenfeld and Bell 2011). On the basis of a centrally located air monitoring station in downtown Atlanta, Lacke et al. (2009) found that on warm-season days dominated by moist tropical air masses, weekends have a lower, less variable concentration of PM 2.5 (particles with an average aerodynamic diameter less than 2.5 μm). A greater and more variable PM 2.5 concentration occurred on weekdays. For this study, we used PM 10 (particles with an average aerodynamic diameter less than 10 μm) concentrations, as the ground-based observational record for this parameter matched the 14 duration of the flash record.

Methods

PM 10 data were obtained from the U.S. EPA Air Quality System for eleven monitoring sites across the northern half of Georgia (Fig. 2). Records at each site were summarized by day of the week for warm-season months (May through September) over the interval 1995–2008. Because of the fourteen-year time frame, none of the PM 10 monitors were continuously in operation, and in some cases, monitoring equipment and measuring methods changed at a site. Monitors are also sensitive to local site conditions. However, data from them have been shown to provide robust interpolations of ambient aerosol conditions over the Atlanta metropolitan region and are routinely used to study the epidemiological impacts of air pollution (Ivy et al. 2008).

Hierarchical agglomerative cluster analysis was used to assign aerosol monitoring sites to groups according to their average PM 10 concentration for each day of the week. Three major clusters were delineated: an urban cluster (5 air monitoring stations), an outlying suburban cluster (4 stations), and a rural cluster (2 stations) with locations east and south of the city.

A multiple response permutation test (MRPP; McCune and Mefford 2009) was used to gauge the strength of this threefold grouping of PM 10 signals. MRPP is a distance-
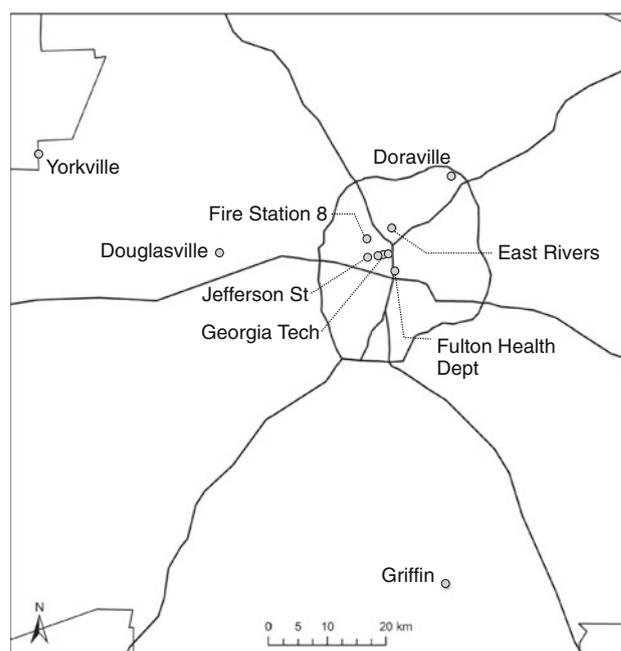

Fig. 2 PM 10 monitoring site locations

based, nonparametric test of group differences. MRPP tested the null hypothesis of no difference among the three clusters of monitoring sites ($n = 11$) based on their average PM 10 concentration for each day of the week. Data values in MRPP are compared based on their proximity derived from a similarity distance metric. For example, observations from a group of sites with the same aerosol regime would have a small average distance, a value calculated from all possible pairs of observations. MRPP compares this average within-group or within-cluster similarity distance to between-cluster similarity distances. The statistical significance of cluster groupings can then be calculated by comparing the observed average within- and between-cluster similarity distances with the distribution of similarity distances obtained from random permutations of cluster membership.

Cloud-to-ground flashes for the northern half of Georgia (1995–2008) were obtained from the National Lightning Detection Network (NLDN; Vaisala Inc.). Five warm-season months, May through September, were analyzed. These 5 months account for approximately 90 % of the annual CG flashes in any single year for the study region. CG flash detection efficiencies for the 1995–2003 period are 80–90 % with a locational accuracy of 500 meters. For 2004–2008, detection efficiencies are 90–95 % and locational accuracies better than 500 meters. Due to upgrades in the NLDN, +CG flashes <10 kA were deleted for the 1995–2003 interval, and +CG flashes <15 kA were removed from the years 2003 through 2008. Rudlosky and Fuelberg (2010) and Orville et al. (2011) provide a recent discussion on these upgrades and their effects.

Flashes occurring when warm moist air mass conditions dominated over synoptic and tropical storm forcings were selected for analysis following the classification system of Sheridan (2002). Days with greater than 50,000 flashes were also removed. Only one day met this category, comprising 71,000 flashes. Large flash outbreaks override local controls, and their segregation has been a common practice in urban lightning studies (Westcott 1995; Steiger et al. 2002; Stallins et al. 2006).

The final pre-analysis data set consisted of 3,249,489 CG flashes over 802 days. In ArcGIS, flash point data were joined to a grid of 2 × 2 km cells covering the study area. These data were imported into a database where queries were performed to select out and summarize grid cell-level flash descriptors before exporting back into ArcGIS for visualization.

Weekdays were defined as Tuesday through Friday. Weekends were Saturday through Monday. There are several reasons for this designation. Weekly aerosol cycles may not necessarily adhere to the workday schedule of humans. Assuming an exact correspondence between the weekday–weekend division in aerosol concentrations across a region with contrasts in human population density is also simplistic. Moreover, comparing each individual day to all others may disaggregate observations in such a way as to obscure the strength of any weekly signal. One could expect that some days are going to be like others. There is also added analytical and narrative clarity in finding and describing trends when there are fewer observational categories than seven. We analyzed our PM data to indicate where a natural break might fall in order to designate weekend and weekday aerosol conditions. Our PM data had lower PM10 concentrations on Saturday, Sunday, and Monday. Plots of particulate matter for Rosenfeld and Bell (2011) also show that these days have the three lowest concentrations over the scale of the conterminous United States.

Since this categorization of weekend (3 days) and weekday (4 days) was unbalanced, we relativized mapped variables to ratios like flash density or percentage. When map values are relative measures instead of absolute counts or totals, they can be compared on a more equitable basis. To facilitate the visual comparison of weekend and weekday maps, color scales were also relativized to maximum observed values. These data relativizations allowed us to make full use of the data while making minimal assumptions about the trends within it. Although one might assume that the selection of Saturday/Sunday as weekend days and its comparison with any two weekdays would provide an unproblematic balanced design, this approach would leave out data and any signal they might contain. It would introduce the criticism that we selected only those days that produced patterns that we wanted to find. Our decision to group days of the week as we did maintained the conservative data use strategy recommended for exploratory study designs.

Doppler radar data were also visualized in order to provide an independent corroboration of our flash results. We compared weekday and weekend reflectivities using NOWrad national composites of WSR-88D radar reflectivity data produced by Weather Services Incorporated (WSI) Corporation. For each individual 2 × 2 km grid cell, we defined 55 dBZ as the minimum value to indicate a high-reflectivity event with the likelihood of strong thunderstorm convection. Final mapped values reflect the number of days a grid cell registered a high-reflectivity event over the fourteen-year study period. Full radar methodology is described in Bentley et al. (2010).

To assess the significance of our results, two post hoc statistical procedures were employed. First, weekday–weekend similarities in the distribution of flash densities and in the percentage of flash days were mapped using a fuzzy kappa algorithm. Kappa statistics are commonly employed to assess the agreement among cells of paired raster maps (Hagen 2003; Hagen-Zanker et al. 2005). Fuzzy kappa examines the neighborhood around an individual cell and then computes a similarity metric to relate them. A cell search distance of 20 km was used to derive individual grid cell similarity. Fuzzy kappa was calculated in Map Comparison Kit software (Hagen-Zanker et al. 2006). Greater similarity (weaker weekday–weekend contrasts) was indicated by grid cell similarity values approaching one. Decreasing similarity (stronger weekday–weekend contrasts) was indicated by similarity values in cells approaching zero.

CG flashes were sampled from three boxes (each 35 × 35 km^2) positioned downwind of the city. These boxes spanned a central city location, the outer suburbs beyond the perimeter interstate highway, and an outlying rural area (Fig. 1). Flash counts and the number of days with flashes were summed for each day of the week for each box. These three data sets were converted to a similarity distance matrix. These individual matrices expressed the observed similarity (on a scale of 0–1) among all 7 days of the week based on the two measured flash properties. The three distance matrices (one for each box) were independently correlated with a model matrix constructed to represent perfect weekday–weekend dissimilarity in flash properties (Fig. 3). These matrix correlations, or Mantel tests, generated a multivariate correlation statistic for each observed location–model matrix comparison. This correlation represents the degree to which flashes from each of the land use boxes correspond to perfect weekday–weekend contrasts. Statistical significance was calculated by comparing the observed correlation with the probability distribution of the correlation coefficients (r_M)

	Sat	Sun	Mon	Tue	Wed	Thu	Fri
Sat	0	0	0	1	1	1	1
Sun	0	0	0	1	1	1	1
Mon	0	0	0	1	1	1	1
Tue	1	1	1	0	0	0	0
Wed	1	1	1	0	0	0	0
Thu	1	1	1	0	0	0	0
Fri	1	1	1	0	0	0	0

Fig. 3 Model matrix for Mantel tests. Sorenson's distance was used to define similarity distances. *Light shaded areas* indicate perfect similarity in weekday and weekend conditions, and Sorenson's distance equals zero. *Darker shaded areas* indicate perfect dissimilarity, and Sorenson's distances are equal to 1

obtained through Monte Carlo randomizations of the data ($n = 999$). PC-Ord Version 5 (McCune and Mefford 2009) was used to perform Mantel tests. The use of Mantel tests to assess the goodness of fit of observed data to a model matrix is reviewed in Legendre and Legendre (1998).

Results

PM 10

Each of the three cluster designations for PM monitoring sites was statistically distinct based on MRPP test statistics (Fig. 4). The downtown cluster of monitoring sites and a perimeter cluster had weekday peaks and overall higher PM 10 values across a week than the rural group (Fig. 5).

To ascertain whether or not CG flashes have any association with PM 10, flashes falling within the central city box were summed by day of the week and correlated with the average observed daily PM 10 value. PM 10 had a robust positive linear correlation with CG flashes (Fig. 6; $r_S = 0.78$, $p = 0.09$). Sunday, Mondays, and Saturdays had fewer flashes and lower PM 10 concentrations. Flash counts and PM 10 peaked on Tuesday and Thursdays. One

should consider Fig. 6 as representing an aggregate snapshot, a validation of the relationship between PM 10 and lightning. Although it suggests a weekly signal, Fig. 6 does not portray the actual geographic variability in a weekly signal, as seen in the following maps.

CG flashes

The location of the maxima in total CG flash density shifted between weekdays and weekends. Weekday flash densities peaked across a broad region around Atlanta and extended eastward in the direction of prevailing winds (Fig. 7). On weekends, flash production diminished in these outlying areas. Total flash production contracted toward the central city, where flash densities remained as high as on weekdays.

A higher percentage of weekday flash days were concentrated in Atlanta and to the east of the city (Fig. 8). Elevated flash days also extended across the northwest of the state. On weekends, flash day maxima contracted toward the central city. The percentage of flash days diminished throughout much of the study area, but remained relatively higher over the city.

The percentage of +CG flashes was expected to decrease on weekdays. The reduction in water droplet size due to competition with urban aerosols and altered updraft–downdraft dynamics is thought to alter the charge structure of thunderstorms so as to decrease the percentage of +CG flashes (Kar et al. 2009; Farias et al. 2009). On weekdays, the percentage of +CG flashes was lower over the city and to the east (Fig. 9). On weekends, the outline and dimensions of this area of lower percentages of positive flashes activity diminished in strength and size but were still visible directly over Atlanta. Grid cells with a higher percentage of +CG flashes emerged outside of the city.

CG flash currents also differed in their strength and distribution between weekends and weekdays. Flash current is measured in kiloamps (kA) and becomes stronger as values become more negative or more positive.
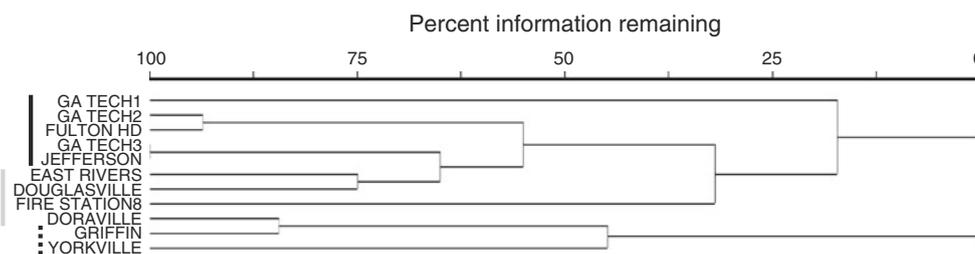

Fig. 4 Dendrogram produced from hierarchical agglomerative cluster analysis of site PM 10 concentrations by day of the week. Three clusters were identified, a downtown cluster (*solid dark line*), a perimeter cluster (*gray line*), and a rural cluster (*dashed line*). On the basis of MRPP results, the statistical strength of this grouping was

strong ($A = 0.14$, $p = 0.08$). When all items are identical within groups, $A = 1$. If contrasts within groups equal expectation by chance, then A approaches 0. Values of A between 0.1 and 0.3 are common for environmental data (McCune and Mefford 2009)
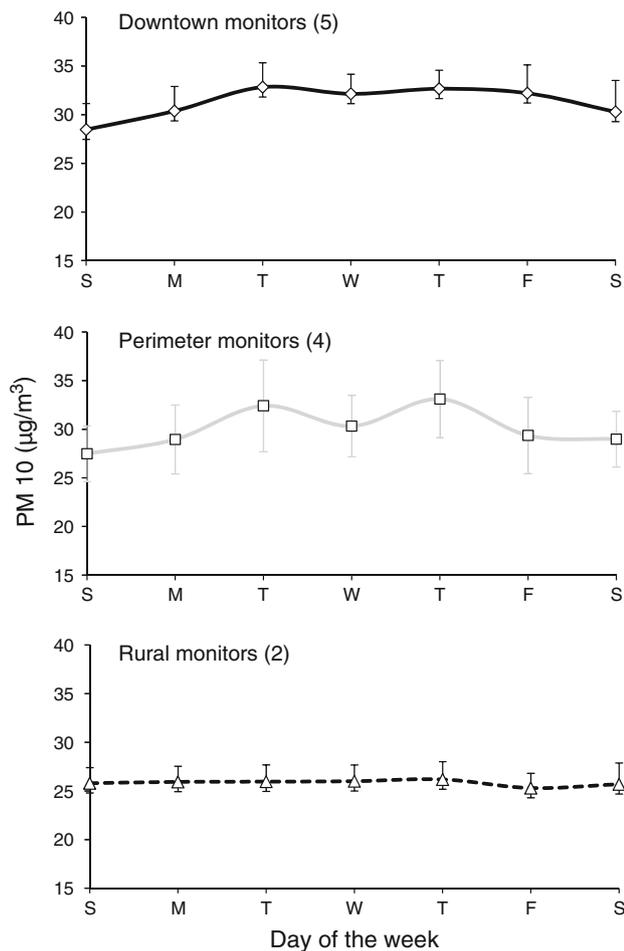
Fig. 5 Day of the week PM 10 concentrations for each of the clusters identified in the dendrogram. Means and standard deviations reflect the central tendency and variability among monitoring sites from top to bottom: (a) downtown—5 sites, (b) perimeter—4 sites, (c) rural—2 sites
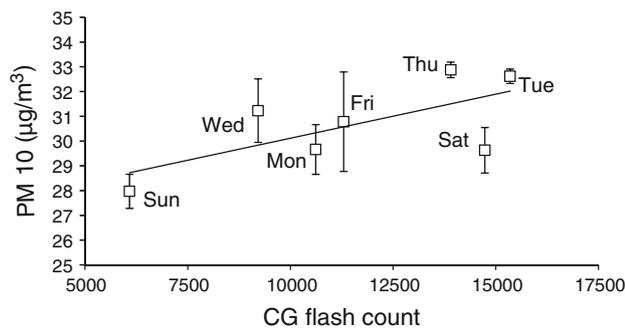

Fig. 6 Scatterplot of average PM 10 concentrations with flashes that fell within the central city box (see Fig. 1). PM averages are derived from the observations from the downtown (5 sites) and perimeter (4 sites) monitoring locations

Fig. 7 Relativized flash counts. Total CG flash density by weekday (2,186,033 total flashes) and weekend (1,063,456 total flashes). *Colors* denote each grid cell's total flash count divided by the respective number of days in its week category (3 for weekends or 4 for weekdays) and expressed in km^2. Grid cells are 2×2 km. Maximum grid cell flash count was 421 for weekdays (*upper map*) and 273 flashes for weekend (*lower map*). This corresponds to values of 26 flashes per weekday per km^2 and 23 flashes per weekend day per km^2 over the study interval. The higher of these two flash densities was selected to standardize visual comparison of the maps

Peak currents closer to zero are considered weaker flashes. Strong +CG and −CG flashes are associated with severe thunderstorms, structural damage from lightning, and fire ignitions. Positive polarity flashes pose more of a hazard because they typically contain a single return stroke, exhibit the greatest peak currents, and produce the largest charge transfers to ground (Rakov 2003; Saba et al. 2006; Rakov and Uman 2003). Positive CG flashes can manifest as "bolts from the blue" that travel through clear air and strike the ground up to 40 km away from a thunderstorm (National Weather Service 2010).

Weekday minimum peak current (toward more negative values) did not have an apparent spatial association with Atlanta (Fig. 10). The minimum was generally between −50 and −100 kA across the entire study area, with a few days recording stronger currents of −100 to −150 kA. For
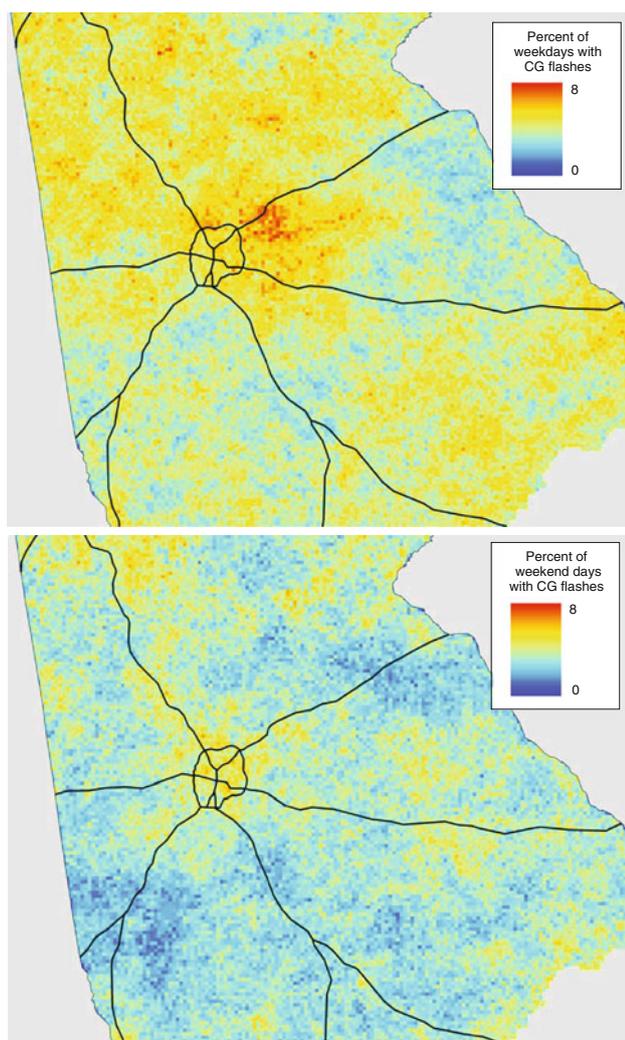
Fig. 8 Relativized flash frequencies. Percentage of CG flash days by weekday (*upper map*) and weekend (*lower map*); 486 weekdays had at least one flash over the study area out of a possible 746 weekdays dominated by moist tropical air masses, and 316 weekends had at least one flash out of a possible 514 days with air mass-dominated conditions. Grid cell *color* represents the number of calendar days with at least one CG flash divided by the respective total number of possible days and expressed as a percent. Maximum grid cell day count for weekdays was 57 (7.6 %). Maximum grid cell day count for weekends was 33 (6.4 %). An upper value of 8 % was selected to standardize visual comparison of the two maps

Fig. 9 Relativized positive flash polarity. Percent +CG flashes by weekday (*upper map*) and weekend (*lower map*). Grid cell values are the number of +CG flashes divided by the total number of +CG and −CG flashes and expressed as a percent. Histograms indicated that percent positive polarities for weekends and weekdays tended to drop off rapidly around 14 %, the value chosen to standardize map comparisons. For weekends, the maximum grid cell values for percent positive had a very long tail. Approximately 163 grid cells (0.8 % out of a total 20,299) had values ranging from 14 to 50 %. Most of these CG flashes were beyond 150 km of the city and tended to be grid cells that had only one or two flashes. Weekdays did not exhibit this long tail. There were only 17 grid cells (0.08 %) with percentages greater than 14 % and no values greater than 25 %. Grid cells with 0 % positive flashes are *highlighted* in *gray*

weekend conditions, however, contrasts in minimum peak current between city and region were evident. Peak currents beyond the proximity of urban land uses became weaker (less negative). Within the inner perimeter of Atlanta (roughly the area contained by its loop interstate highway; see Fig. 1), minimum peak currents remained more strongly negative and similar to weekday levels.

On weekdays, the highest positive daily peak currents did not have an association with Atlanta (Fig. 11). They were uniformly positive and under 100 kA across city and region. However, weekend maxima exhibited city–region differ-
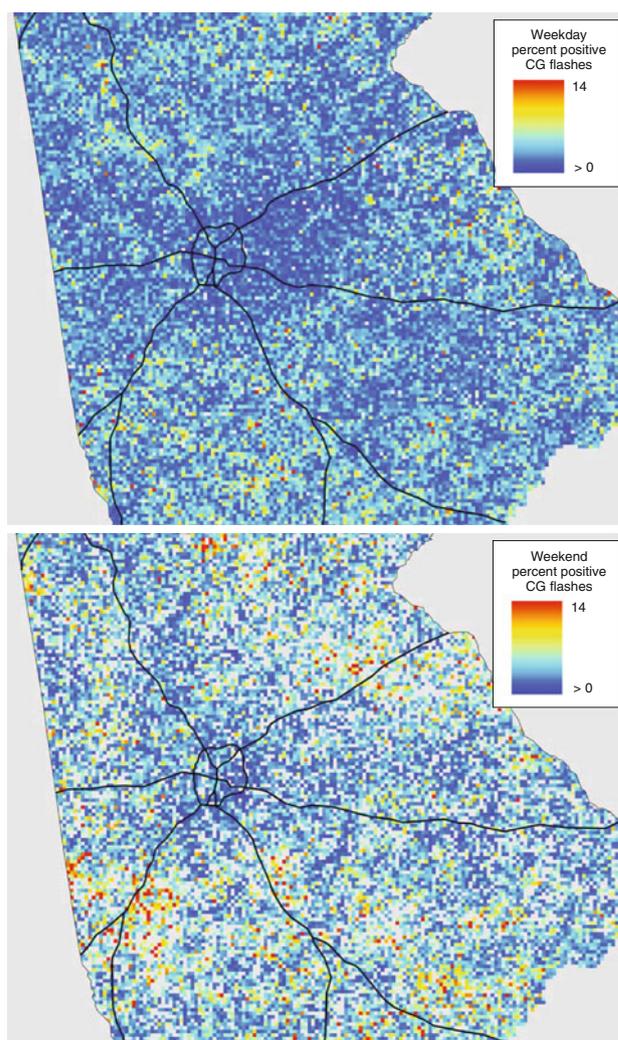
entiation. Positive peak current across the region decreased (weakened) toward zero and in some cases became negative where no positive flashes were observed. This decrease was not evident around the city, where maximum peak currents remained stronger and more positive, but still generally less than 100 kA. As observed for negative peak currents, the greatest contrast between weekday and weekend positive peak current was outside of the city. Immediately over the
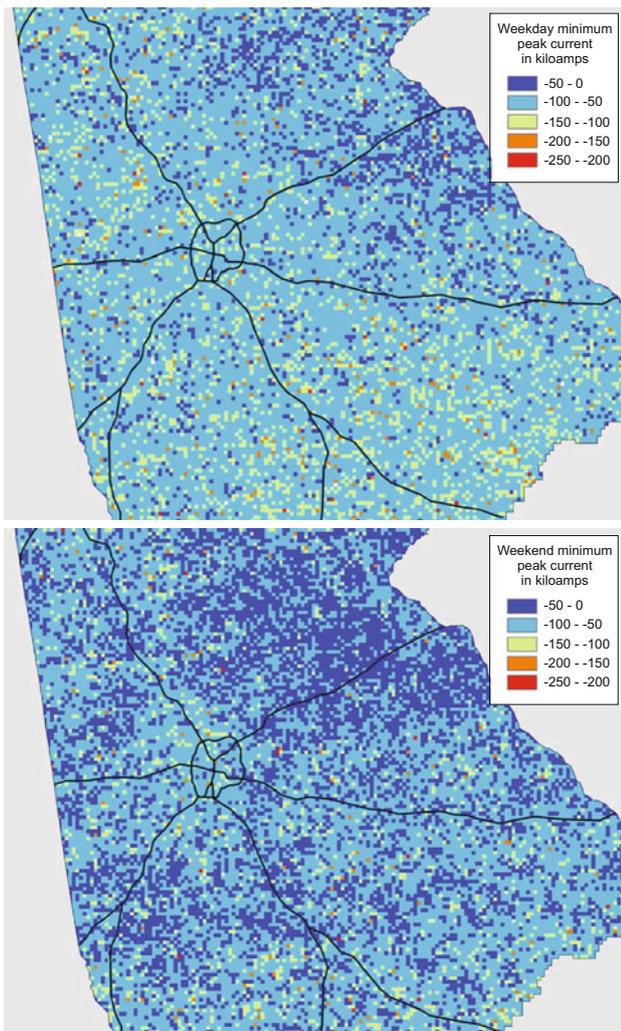
Fig. 10 Daily minimum peak currents in kiloamps (*kA*) for weekday (*upper map*) and weekend (*lower map*). Weekdays had stronger (more negative) flashes across the entire study region. In the city, weekday and weekend contrasts in minimum peak current were diminished. There was a propensity for stronger −CG flashes on weekends as well as weekdays

Fig. 11 Daily maximum peak currents in kiloamps (*kA*) for weekends (*upper map*) and weekday (*lower map*). Flashes <15 kA may be considered cloud-to-cloud and were removed from the data set. The rare peak currents greater than +254 kA can be considered artifacts of the detection network that existed prior to upgrades in 2003

city and within the inner perimeter, weekend peak currents differed little from what occurs on weekdays. There was a propensity for stronger positive and negative peak currents over the course of a week.

High radar reflectivity event counts confirmed that convective intensity maxima differed between weekday and weekend conditions (Fig. 12). A higher percentage of reflectivity peaks were located over the city and just to the north and west on weekdays. On weekends, high reflectivities around the city were not as evident.

Post hoc statistical tests

Fuzzy kappa mapping of the similarity between weekday and weekend grid cell values for total flash density (see
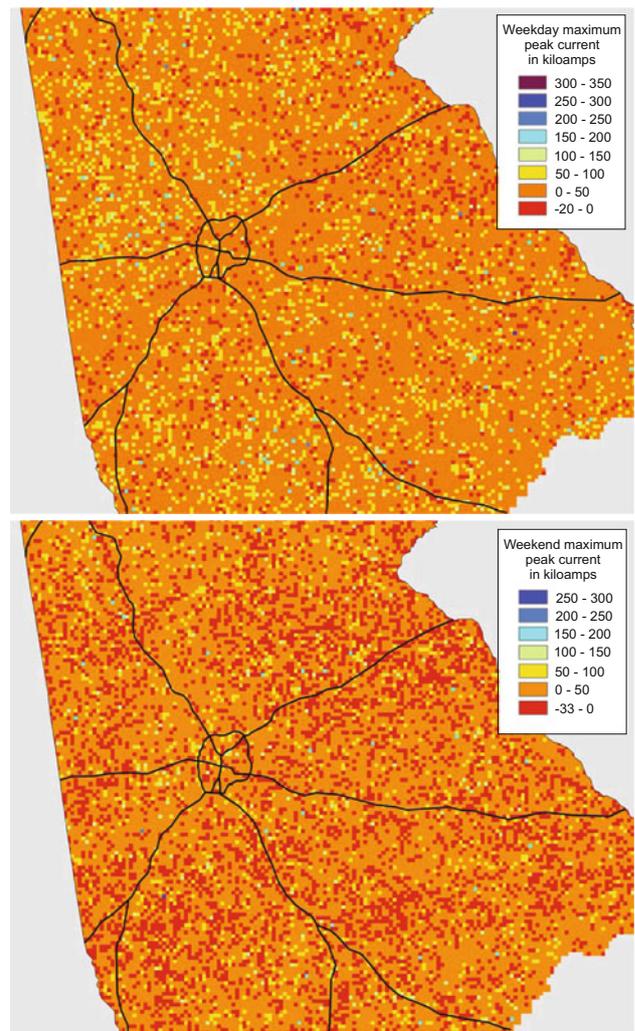
Fig. 7) and flash days (see Fig. 8) indicated a complex, but structured pattern of weekly signals (Fig. 13). Within Atlanta's perimeter loop interstate highway, kappa similarities for weekday and weekend flashes remained high, likely because of uniformly elevated anthropogenic influences throughout the week. Any weekly signal was muted. Rural areas well outside the city also had high kappa similarities. However, here it is likely a consequence of aerosol concentrations and flash activity that are uniformly reduced throughout the week. In between these two locations is a discontinuous ring of values indicating low similarity and thus stronger contrasts in weekend and weekday flash production. Here, on the periphery of the urban core, but within the surrounding rural land cover, the weekend signal was the strongest. More variability in aerosol conditions is a likely explanation for this reduction
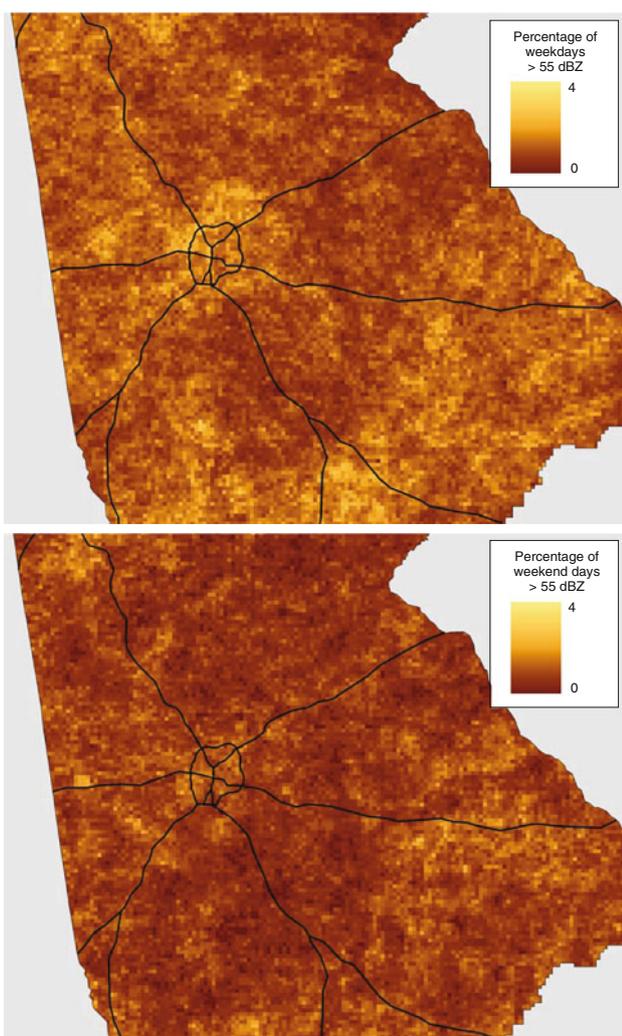
Fig. 12 Relativized radar reflectivity day counts for weekdays (*upper map*) and weekend days (*lower map*). Grid cells represent the number of days having a reflectivity >55 dBZ divided by the total number of air mass days for that respective day of the week category (weekdays = 746 days, weekends = 514 days) and expressed as a percent. The maximum grid cell count for weekdays was 29 days (3.9 %) and for weekends was 22 days (4.3 %). A value of 4 % was chosen to standardize the color scales for their comparison

Fig. 13 (Colour figure online) Distribution of weekday to weekend similarity for total flash density (*upper map*) and percentage of flash days (*lower map*). *Colors* and their numerical values indicate the strength of weekday–weekend contrasts. *Green shades* and values closer to one are indicative of minimal weekday–weekend contrasts. *Red shades* and values approaching zero are indicative of greater weekday–weekend contrasts. Unlike Sorenson's distances, similarity in the fuzzy kappa algorithm is reversed: 0—maximum dissimilarity, 1—maximum similarity (color figure online)

in similarity across a week, although interactions with thermodynamically forced circulations likely play a role.

The CG flashes from the boxes over the central city, suburban, and rural land uses affirmed these general trends in flash properties across a week duration (Fig. 14). Mantel tests confirmed that the suburban location outside of the perimeter interstate had the strongest correlation ($r_M = 0.73$, $p = 0.03$) with the model matrix representing perfect weekday–weekend contrasts. Rural observations were weak ($r_M = -0.22$, $p = 0.06$), but still slightly stronger than the central city ($r_M = -0.04$, $p = 0.50$). In sum, kappa statistics and Mantel tests confirmed Bell et al.'s (2009a) observation of greater weekend–weekday contrasts
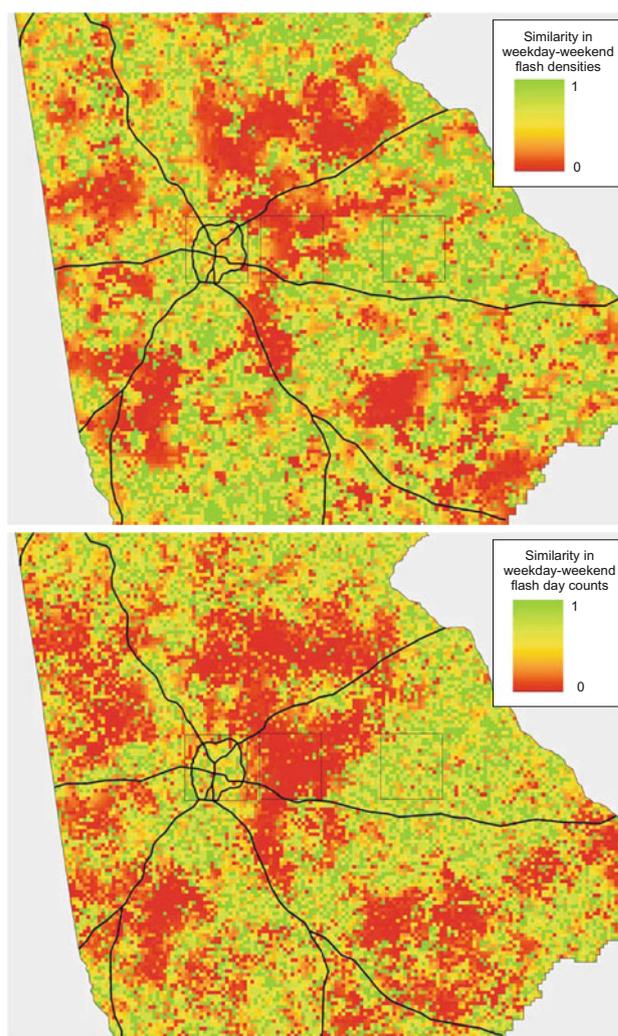
outside of the urban core. Rural locations in this study may even have a stronger weekly signal than the city, although the city retains more overall anthropogenic modification.

Discussion

Weekdays were characterized by altered CG flash production within a 100 km^2 radius of the city center. Higher flash densities, higher percentages of flash days, and a lower percentage of +CG flashes developed over the city and extended downwind and beyond urban land covers on Tuesdays through Fridays. Weekends resembled weekdays
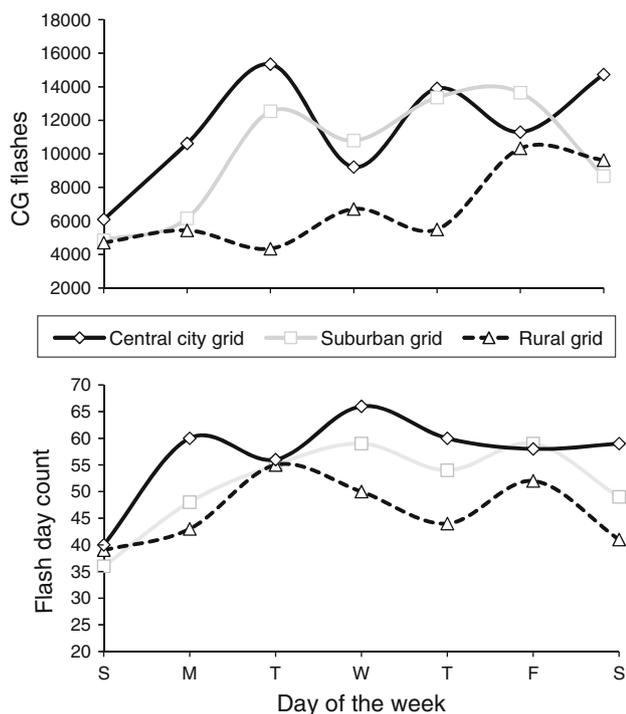
Fig. 14 The number of days with flashes (*upper*) and total flash counts (*lower*) for individual days of the week in the three small rectangular boxes shown in Fig. 1

in terms of CG lightning but only within the urban area enclosed by perimeter interstate highway that encircles Atlanta. Instead, the greatest weekday–weekend contrasts developed on the outside of the city perimeter in more suburban land uses. Here, weekends exhibited a decrease in flash density and in the percentage of flash days and +CG flashes.

There was also evidence in this study for a broader regionalization of aerosol influences on CG lightning. Except for the area immediately over Atlanta, weekends and weekdays underwent a widespread shift in the distribution and magnitude of peak currents. Weekdays had stronger positive and negative peak currents. Weekend currents shifted in the direction of weaker flashes, toward values closer to zero.

These results support studies postulating how weekly weather signals may not necessarily be confined to urban areas (Baumer and Vogel 2007a, b; Bell et al. 2009a; Rosenfeld and Bell 2011). Our quantification of the similarity between weekday and weekend flash properties detailed how weekly signals are heterogeneously distributed. The urban core had no weekly signal, although it experiences the most modified CG flash production. This may be due to the week-long persistence of anthropogenic aerosols and thermodynamic properties within the city proper. Thus, the expectation of cities being the best place to find weekly signals is not necessarily true. The more pronounced weekly signal appeared outside of Atlanta, in

the form of a discontinuous ring of strong contrasts between high midweek flash production and lower values on weekends. This zone of greater weekday–weekend dissimilarity resembles Petersen and Rutledge's (2001) observation of greater spatial variability and structure to convective processes where aerosol regimes are more variable.

To conceptualize our findings, and to express them in a manner useful for other urban weather studies, we constructed a graphical model showing how weekly signals may change over time and space for an idealized city (Fig. 15). The goal of this model is to convey the potential heterogeneity in weekly signals. It captures how weekend–weekday contrasts in the city center can be low, but still reflect anthropogenic modification. Moreover, it also communicates how weekend–weekday effects can appear, disappear, and reappear in different parts of the city and region as a city expands. We emphasize that this model does not necessarily proscribe a linear timeline or sequence of inviolable stages, nor should it be taken as universally applicable. Weekday–weekend effects are a dynamic phenomenon. They are variable in time given the contingencies of growth, land use geometry, and physical setting.

In this model, we simplified a city into an urban core dominated by impervious cover encircled by more mixed land uses that approximate suburban settings. The outer or background land use is rural. In the first stage, a weekday–weekend signal in convective phenomena may not be expressed. Such pristine conditions may be difficult to verify, and dates will vary from city to city and with different criteria. For Atlanta, the late 1970s may have marked the most recent change in urban–suburban growth that modified local climates (Diem and Mote 2005). In the second stage, increasing urban land cover, surface roughness, and aerosol concentrations may begin to modify weekday weather and climate. A weekday–weekend contrast may emerge over the central city because weekends in the city have not developed the intensity of anthropogenic conditions for weather modification. However, as the urban area expands, weekends can become more like weekdays over the city center. In this third stage, weekend–weekday contrasts diminish in the city even though there may be substantial anthropogenic modification of convective phenomena like rainfall or lightning. The weekly signal reappears in the ring just outside of the urban core. Here, weekends still experience a clearing of urban aerosols. In the next stage, concentrations of aerosols may reach a point in the urban core where radiatively forced cooling from aerosols may diminish instability and convective potential on weekdays. A weekly signal may reemerge as weekends in the urban core have not yet reached the threshold concentration of aerosols to initiate negative feedbacks. Increasing weekend pollution in the mixed-use suburban
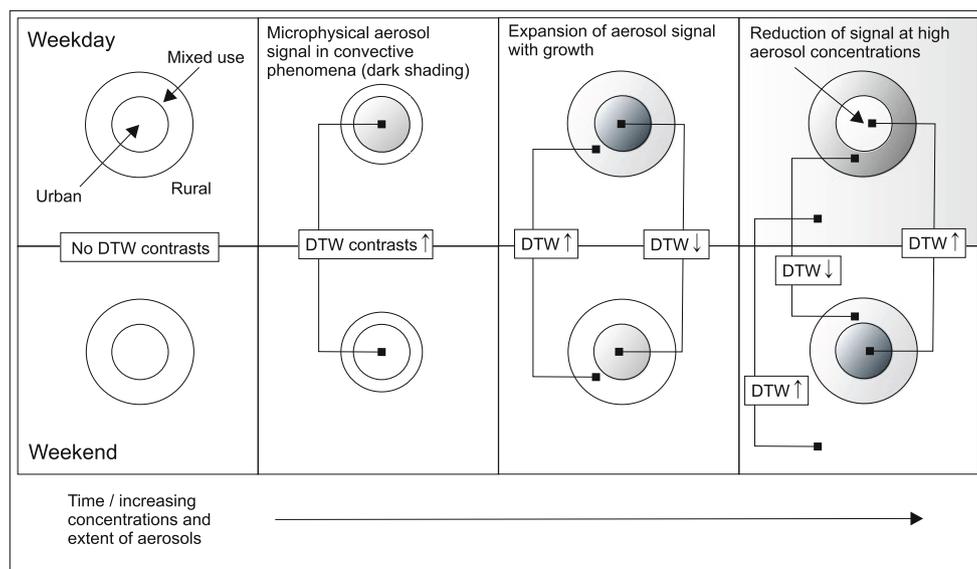
Fig. 15 Conceptual model of the scalar evolution of urban–regional anthropogenic aerosol effects. DTW indicates day of the week; *arrows* reflect whether the contrasts between weekdays and weekends are strong or increasing versus weak or decreasing. Given the range of development trajectories among cities in North America, the idiosyncratic positions of point source origins of aerosols like power plants and major roadways, and the variability in atmospheric transport, one could expect to see a more complex spatial and temporal weekend signal than idealized here

ring may diminish the weekly signal relative to the one expressed in the urban core. At this point or earlier, regional weekend–weekday contrasts may develop if aerosols are widespread and of sufficient concentration to alter weekday conditions.

Closing

Our characterization of the geographic variability in a weekly lightning signal also has applied relevance. Lightning hazards around urban areas may be more heterogeneously distributed. Given that weekend and weekday lightning for the urban core is elevated, lightning hazards there may be more persistent across a week. More flashes and stronger peak currents should increase the risk of exposure and property loss (Curran et al. 2009; Ashley and Gilson 2009). On the other hand, the lightning hazards that develop outside the urban core in suburban-transitional land uses are a consequence of a more variable convective environment. Hazards arise out of a changeable lightning regime in these more suburban locations. With a greater range in lightning characteristics over a week, outlying suburban areas may have an underacknowledged unpredictability to account for in emergency planning, public safety, and the management of electrically sensitive infrastructure.

Our study shows how detection of weekday–weekend effects can be dependent upon the spatial extent of analysis and the degree of anthropogenic modification of the urban atmosphere. For example, if one conducted a study just of the Atlanta within its perimeter highway, no weekly signal would be evident. Yet at larger continental scales, one may begin to see the influence of more hemispheric aerosol contributions at the expense of losing the detail around populated areas. Moreover, if one considers the spatial heterogeneity that can develop in a weekly signal as we have characterized, it might be possible that some of the contradictory findings about weekly signals in rainfall may actually be more compatible (Tuttle and Carbone 2011). The conceptual model we developed from our observations is an attempt to facilitate interpretation of the range of patterns and processes associated with urban weather and climate (e.g., Ren et al. 2010).

Our findings add more city-specific detail to the continental-scale work of Bell et al. (2009a). Their hypothesis that urban areas may not have a strong weekly lightning signal because of indistinct weekday–weekend atmospheric environmental conditions was shown to have validity at the finer scales employed in this study. We detailed how the weekend–weekday signal may be more pronounced in nonurban regions, and how the location of weekday–weekend signals can fade and reemerge as cities and their environmental context change. At the heart of the challenge of characterizing weekly signals is the scale problem of isolating patterns from processes operating over different scales, and interpolating among analyses conducted at a range of spatial extents and resolutions.

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