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Concurrent Cloud-to-Ground Lightning and Precipitation Enhancement in the Atlanta, Georgia (United States), Urban Region

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ABSTRACT: This study explores how the Atlanta, Georgia (United States), urban region influences warm-season (May through September) cloud-to-ground lightning flashes and precipitation. Eight years (1995–2003) of flashes from the National Lightning Detection Network and mean accumulated precipitation from the North American Regional Reanalysis model were mapped under seven different wind speed and direction combinations derived from cluster analysis. Overlays of these data affirmed a consistent coupling of lightning and precipitation enhancement around Atlanta. Maxima in precipitation and lightning shifted in response to changes in wind direction. Differences in the patterns of flash metrics (flash counts versus thunderstorm counts), the absence of any strong urban signal in the flashes of individual thunderstorms,

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and the scales over which flashes and precipitation enhancement developed are discussed in light of their support for land-cover- and aerosol-based mechanisms of urban weather modification. This study verifies Atlanta's propensity to conjointly enhance cloud-to-ground lightning and precipitation production in the absence of strong synoptic forcing. However, because of variability in aerosol characteristics and the dynamics of land use change, it may be a simplification to assume that this observed enhancement will be persistent across all scales of analysis.

KEYWORDS: Atlanta; Lightning; Precipitation

1. Introduction

Land-use conversion is an agent of weather and climate modification (Pielke 2002; Pielke et al. 2007). Urban areas are recognized for their propensity to alter convective activity (Changnon et al. 1971; Huff and Changnon 1973; Trenberth et al. 2007). Conversion of forested and agricultural land to urban and suburban cover has been associated with the development of urban heat islands (Oke 1973; Arnfield 2003; Grimmond 2007; Yow 2007), changes in rainfall intensity and distribution (Shepherd 2005; Rosenfeld et al. 2007a; Pielke et al. 2007), and altered cloud-to-ground (CG) lightning production (Westcott 1995; Steiger et al. 2002; Stallins et al. 2006; Kar et al. 2007).

This study documents concurrent cloud-to-ground lightning flashes and precipitation in the Atlanta, Georgia, urban region. Atlanta is well suited for an examination of how anthropogenic land uses influence precipitation and lightning because of its distance from immediate sea-breeze effects, its prominent urban heat island, and the multidecade conversion (1970s to present) of large tracts of rural lands, particularly in Cobb, Dekalb, Fulton, and Gwinnett counties (Figure 1). Atlanta's urban land uses modify convective processes (Bornstein and Lin 2000; Craig and Bornstein 2002), precipitation distribution (Bornstein and Lin 2000; Dixon and Mote 2003; Mote et al. 2007; Diem 2008), and peaks in lightning production (Watson and Holle 1996; Stallins et al. 2006; Stallins and Bentley 2006). Even though precipitation and lightning originate from the same convective processes, no urban studies have examined these two phenomena in tandem. In this paper, cloud-to-ground flashes and precipitation are characterized for the Atlanta region under different steering wind conditions. Aerosol- and land-cover-based explanatory frameworks are then compared and contrasted in light of observed geographic patterns of flashes and precipitation.

2. Background

Cloud-to-ground flash enhancement has been observed within and downwind of large urban areas spanning a range of latitudes, including the central United States (Chicago, St. Louis, and other cities; Westcott 1995); Brazil (São Paulo and Belo Horizonte; Naccarato et al. 2003; Pinto et al. 2004); Houston, Texas, and Baton Rouge, Louisiana (Orville et al. 2001; Steiger and Orville 2003; Gauthier et al. 2005); Baltimore, Maryland (Ntelekos et al. 2007); and Seoul, South Korea (Kar et al. 2007). Three nonexclusive mechanisms are hypothesized to explain the increase in flashes around cities (Orville et al. 2001). First, anthropogenic heating

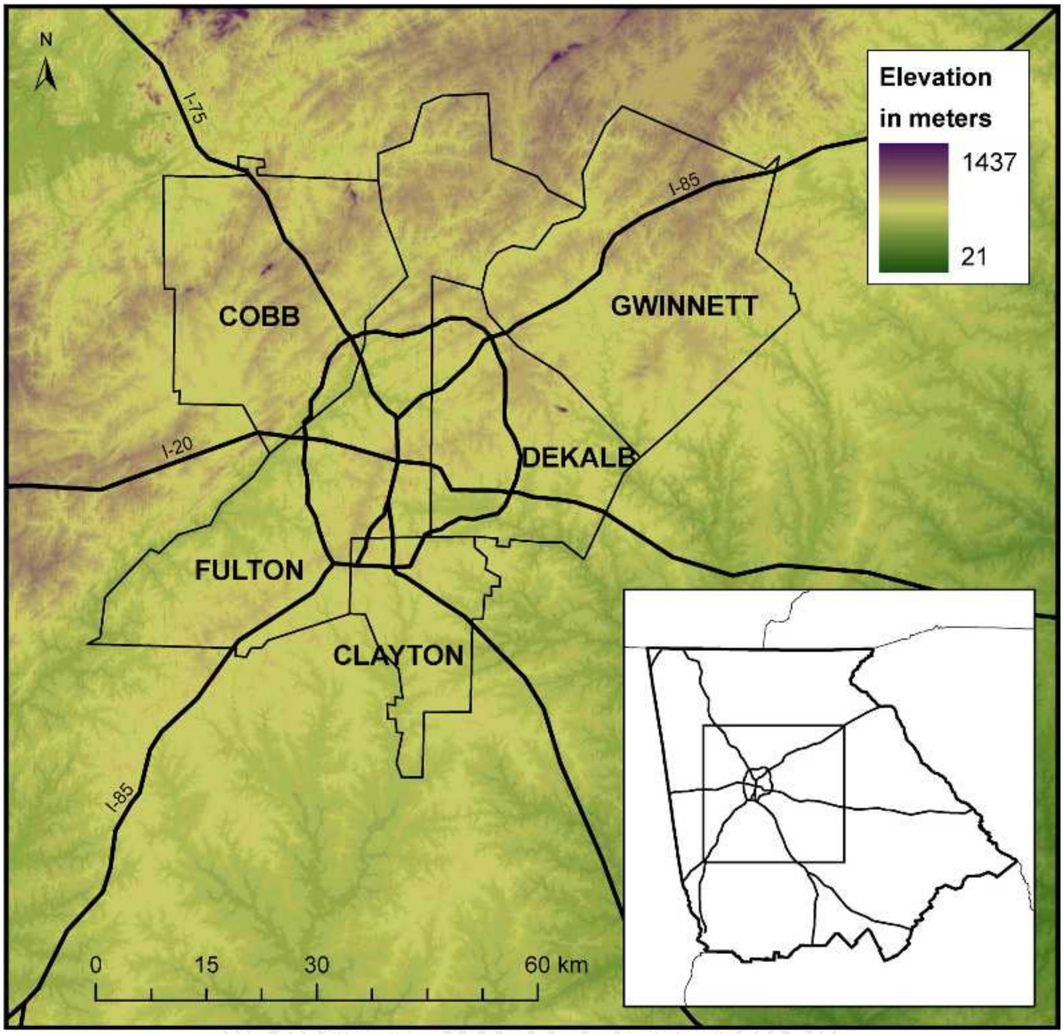

Figure 1. Study area topography, interstate highways, and the five most densely populated counties comprising Atlanta, Georgia.

and moisture may enhance instability and facilitate urban-forced convergence. Second, surface roughness attributed to the built environment can enhance wind convergence and the dynamical conditions for thunderstorm development. Third, urban aerosols may alter lightning production by modifying the dynamics of hydrometeors. Aerosol-based mechanisms of urban weather modification evolved out of studies exploring how continental and maritime aerosols shape cloud dynamics and precipitation at larger spatial scales (Williams et al. 2002; Williams et al. 2005). Aerosols slow the collision–coalescence process and cause more liquid water to be transported to higher levels where it freezes and subsequently interacts with other hydrometeors in the noninductive charge separation process. Urban particulate matter has been associated with greater overall flash counts, more flash days, and lower percentages of positive polarity flashes (Stallins et al. 2006; Steiger et al. 2002). However, thunderstorms ingesting very small aerosols created by forest fires have higher percentages of positive polarity flashes (Rosenfeld et al. 2007b).

Lowry (Lowry 1998) summarizes the first wave of urban climate studies that characterized precipitation anomalies among several U.S. and European cities. More recently, anthropogenic precipitation enhancement has been observed in Taipei (Chen et al. 2007), Mexico City (Jauregui and Romales 1996), Phoenix (Diem and Brown 2003; Shepherd 2006), Houston (Burian and Shepherd 2005; Shepherd and Burian 2003), Atlanta (Mote et al. 2007; Diem 2008), and across the southeastern United States (Bell et al. 2008). The same three casual factors identified for lightning—urban heating and moisture content, surface roughness, and aerosols—are also hypothesized to influence urban precipitation. The effects of aerosols on precipitation may be dependent upon the diameter of aerosols (Rosenfeld and Givati 2006) and their concentration (Van Den Heever and Cotton 2007). Coarser aerosols may enhance precipitation more immediately, while ultrafine aerosols (submicron) may suppress precipitation (Rosenfeld and Givati 2006; Rosenfeld et al. 2007b). Initial suppression, however, may indirectly lead to enhanced rainfall. Suppressed rainout in the presence of fine aerosols allows droplets to reach greater heights where their freezing can release more latent heat and further invigorate cloud updrafts (Rosenfeld 2006). Thus, the initial delay in the onset of precipitation may eventually lead to greater rainfall (and lightning) production via this secondary storm invigoration. However, as background aerosol concentrations increase, overall aerosol effectiveness in suppressing rainfall may decline (Van Den Heever and Cotton 2007).

Modeling studies have added more evidence as to how urban land–atmosphere characteristics can initiate and enhance convection and precipitation. Nonlinear interactions among surface friction, momentum drag, and urban heating can induce downwind convergence (Rozoff et al. 2003). Urban heating may lead to the formation of a downwind updraft cell that strengthens as boundary layer stability or wind speed decreases (Baik et al. 2001; Baik et al. 2007). As urban heating intensifies, precipitation may move closer to the source of heating (Thielen et al. 2000). Aerosol size and concentration, once convection develops, can exert a strong influence on the strength and timing of updrafts, downdrafts, and the location of precipitation (Van Den Heever and Cotton 2007). Reconciling the nonlinear interactions among aerosols and convective dynamics remains a challenge (Van Den Heever and Cotton 2007).

Although lightning and precipitation originate from the same initial convective and microphysical processes, most urban research has focused only on one or the other of these two phenomena (Stallins and Rose 2008). This study integrates cloud-to-ground flashes with reanalysis data for accumulated precipitation to examine how they covary. Visualizations for warm-season flashes and precipitation were constructed for different combinations of steering winds and speeds and at two scales: climatic (composites of many dates) and at the scale of individual thunderstorm events. By incorporating the general motion of individual thunderstorms and multiple scales of pattern characterization, this paper aims to provide more observational evidence for the variability of anthropogenically enhanced CG flash and precipitation production in and around Atlanta. The geographic patterns distilled through this analytical design are assessed in light of aerosol- and land-cover-based explanatory frameworks.

3. Study area

Atlanta's current metropolitan population of 5.1 million reflects several decades of rapid and spatially extensive conversion of land from pervious to impervious surface (Figure 2). Land-use change in Atlanta and its urban heat island were documented as part of Project Atlanta (Quattrochi and Luvall 2008). Between 1973 and 1997, forest and cropland in the greater Atlanta area decreased by about 20%, while high- and low-density urban land had areal increases of 89% and 119% (Yang and Lo 2002). Previous work by the authors has established a baseline urban CG lightning climatology for the region (Stallins and Bentley 2006; Stallins et al. 2006). Annual average cloud-to-ground flash densities (1992–2003) around Atlanta are on the order of 6–8 flashes per square kilometer per year. Flash production peaks over the northeast corridor of the city, an area of high-density urban and

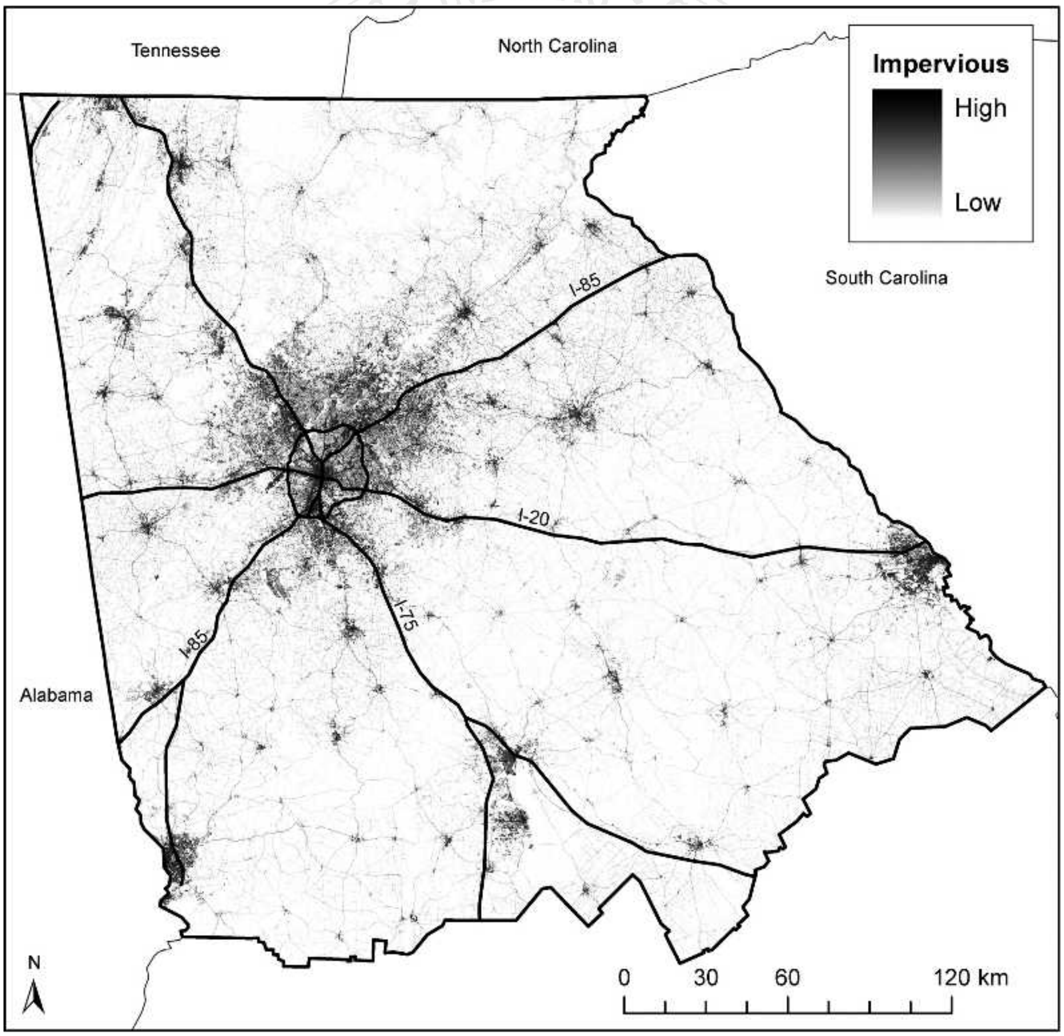

Figure 2. Per-pixel estimates of percent imperviousness for the northern half of Georgia (USGS 2001; Homer et al. 2004). Pixel size is 30 m.

suburban land uses. Relief is mild in the vicinity of Atlanta. Small topographic breaks run along parallel ridges trending southwest–northeast across the city. Spatial regressions of elevation and flashes have indicated no direct significant influence of elevation on flashes in the Atlanta area.

Precipitation increases have also been observed northeast of the city (Diem and Mote 2005; Mote et al. 2007; Diem 2008). A variety of methods, at different spatial extents, time frames, and data resolutions have detected this enhancement. Mote et al. (Mote et al. 2007) employed Doppler radar data. Diem (Diem 2008) and Diem and Mote (Diem and Mote 2005) used ground-based precipitation observations. Shepherd et al. (Shepherd et al. 2002) mapped mean conditional rainfall rates derived from Tropical Rainfall Measuring Mission (TRMM) data and found precipitation enhancement more to the south-southeast of the city. Dixon and Mote (Dixon and Mote 2003) integrated a variety of ground-based and remotely sensed data and detected urban-influenced precipitation events at numerous locations around Atlanta. Most were to the north of the city center. Fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5) simulations (Craig and Bornstein 2002) resolved urban precipitation events to the northeast, east, and south of Atlanta. Bornstein and Lin's (Bornstein and Lin 2000) event reconstructions also found evidence for urban heat island–driven wind convergence to the northeast of the city.

4. Methodology

4.1. Flash data

Flash data for the state of Georgia were obtained from the U.S. National Lightning Detection Network (NLDN; Vaisala, Inc.) for the years 1992–2003. Upgrades to the NLDN 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 these upgrades, CG flash detection efficiency was 70% with a locational accuracy of 5–10 km. Additional upgrades in 2002 and 2003 resulted in flash detection frequencies of 90% or better (Grogan 2004). As recommended by Cummins et al. (Cummins et al. 1998), positive flashes <10 kA were deleted from the dataset. Flash data were mapped in their native format, with no smoothing or estimator-based algorithms.

4.2. Thunderstorm types

For each flash, we classified the day of its occurrence as either weakly or strongly forced based on the National Oceanic and Atmospheric Administration's (NOAA's) Daily Weather Map Series. When a synoptic-scale frontal boundary was beyond 500 km of Georgia, the flashes produced on this day were classified as weakly forced, that is, lacking frontally associated instability and upper-atmospheric support. A frontal boundary within this distance designated a strongly forced day. Previous work has suggested that weakly forced thunderstorms associated with local airmass instability have flash patterns more tightly correlated with the location or low- and high-density urban land covers (Naccarato et al. 2003; Stallins and Bentley 2006). Only nontropical weakly forced airmass thunderstorm events were retained for analysis.

Proof Only

4.3. Flash event tracks

Next, individual flashes were assigned to a thunderstorm event. Each flash in our NLDN dataset was grouped into individual thunderstorm events by means of a temporal and spatial clustering algorithm. Flashes occurring within 15 km and within 15 min of each other were assigned to the same event. Renner (Renner 1998), Bertram and Mayr (Bertram and Mayr 2004), and Tuomi and Larjavaara (Tuomi and Larjavaara 2005) employed similar flash grouping methods.

4.4. Incorporation into a GIS

Flash data were imported into ArcGIS 9.2 (Environmental Systems Research Institute 2007) and binned at a resolution of 2 km × 2 km. Using spatial query functions in ArcGIS Spatial Analyst, a subset of flashes that fell within the hotspot of flash production in northeast Atlanta was selected. The hotspot location, shape, and dimensions were derived from Stallins and Bentley (Stallins and Bentley 2006) and Stallins et al. (Stallins et al. 2006). Flashes selected from this hotspot were then linked to the other cloud-to-ground strikes belonging to the same event and lowered anywhere in the study area. Thus, the analysis dataset was conditioned to contain flashes for each individual thunderstorm event that generated at least one flash in the flash hotspot. Because events having 11 or more flashes accounted for 99% of the total flashes, events with 10 or fewer flashes were dropped from further analysis (Table 1). The 1992–94 events were deselected as the lower pre-1995 accuracy generated coarsely defined individual flash tracks.

4.5. Clustering of flash events according to steering winds

Thunderstorm flash track events were matched with their 700-mb winds (Hand and Shepherd 2008) by way of sounding data from 0000 and 1200 UTC daily radiosonde launches at the Peachtree City National Weather Service office, approximately 50 km south of Atlanta. Stratifying our visualizations according to different combinations of midlevel wind directions and speeds facilitated a more robust assessment as to the extent and covariation of flash and precipitation modification. Wind speeds and directions for each event were first converted to u and v wind vector components. Vector components for each event were then clustered through a partitioning algorithm known as partition around medoids (PAM). The PAM clustering method (Kaufman and Rousseeuw 1990) relies upon a user-defined number of classes. Seven clusters were found to be adequate for capturing a range of wind speeds and directions. In this manner, upwind and downwind positions are relative to the wind cluster under consideration. Upwind and downwind positions are more variable and not constrained only to the predominant wind flow bearing. Clustering was performed in S-PLUS (Insightful Corporation 2002). After accounting for the dates without radiosonde data, the final analysis dataset contained 320 events comprising 654 835 flashes for the northern half of Georgia.

4.6. Data integration and visualization

To examine how lightning production changed among different designations of upwind versus downwind positions of the city, flashes for each of the seven wind

Table 1. Adaptive sampling procedure used to derive analysis dataset. Initial study extent is northern half of Georgia (1992–2003) for the months of May through September.

Attributes	Flashes	Events
Initial dataset	910 507	1034
Only events with >10 flashes	909 285	435
Only post-1994 flashes	825 993	353
Only events with weak forcing	710 570	342
Only flashes with sounding data	654 835	320

clusters and for each of the 320 individual events were mapped in ArcGIS. Individual event maps were visually assessed for evidence of urban influences. This evidence was defined as those events that 1) initiated or rejuvenated lightning production as it neared or passed over the Atlanta urban area; 2) exhibited a spatial pattern of flashes that corresponded to anthropogenic surface features like roadways, airports, or large areas of impervious surface; and 3) had flash activity that was limited to the Atlanta urban area alone. Wind cluster composites and indi-

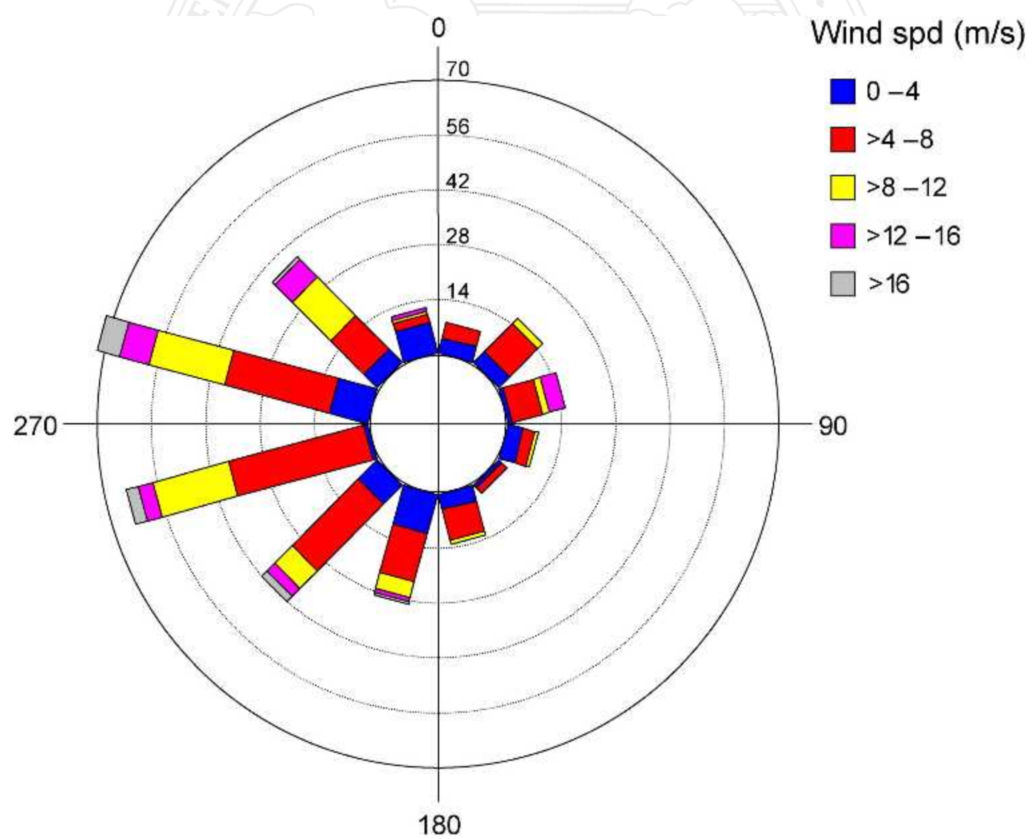

Figure 3. Circular classification of all individual thunderstorm events by steering wind direction and wind speed. Concentric circles represent the number of events (320 events total).

vidual flash events were mapped according to two flash descriptors: flash intensity (the number of flashes) and flash frequency (number of thunderstorm events with lightning). Flash data are presented in classed choropleth maps. Choropleth maps involve the selection of a method to break down interval data into discrete classes. The Jenks natural breaks optimization method was selected, as this classification procedure emphasizes the inherent breaks in the data (Jenks 1967; Campbell 2001).

4.7. Precipitation data

Accumulated precipitation was obtained from the National Centers for Environmental Prediction (NCEP) North American Regional Reanalysis data model

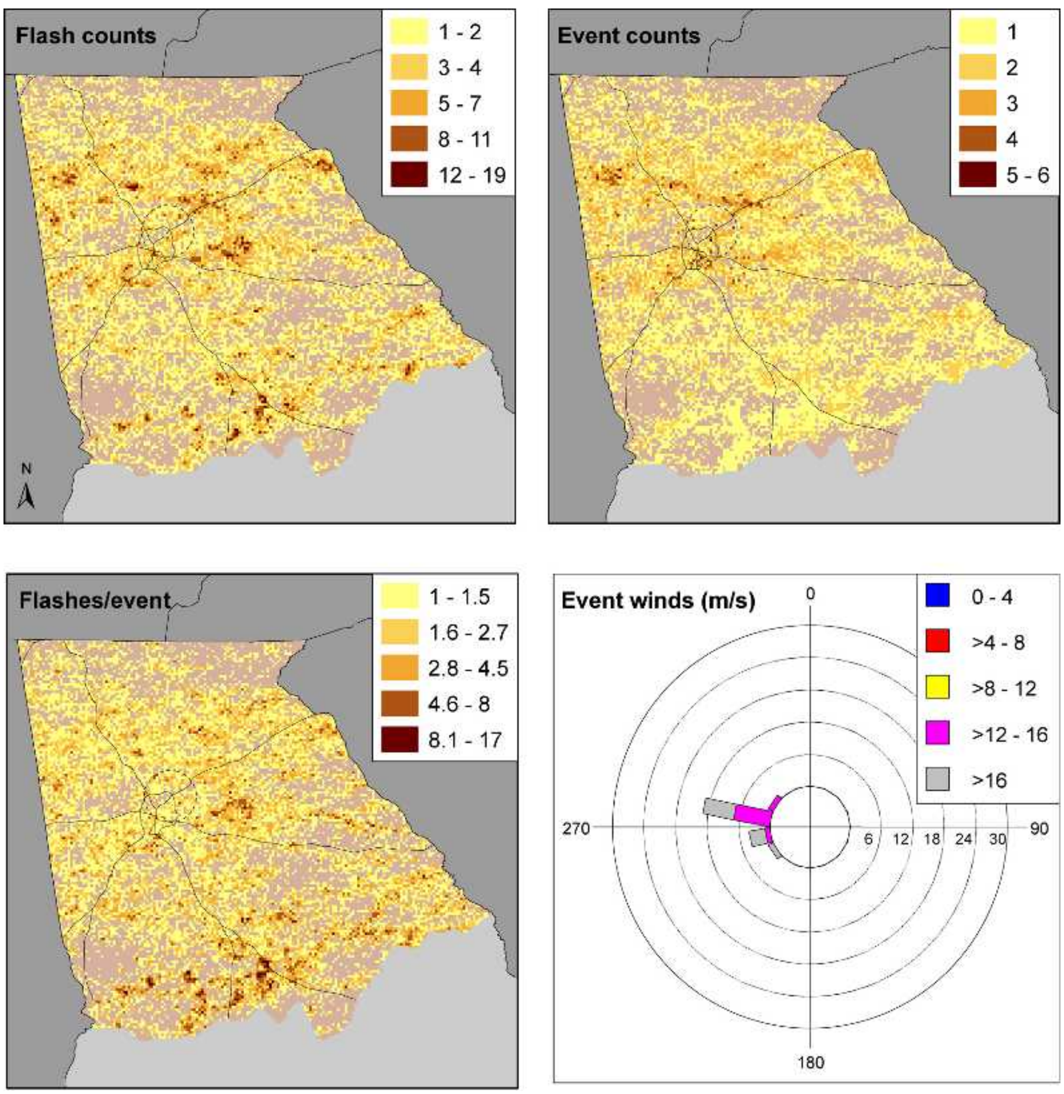

Figure 4. Flash metrics for cluster 1 (west-northwesterly 700-mb flow) and wind rose of individual events. Concentric scale on the *x* axis represents the number of individual thunderstorm events.

Fig. 4 live 4/C

Table 2. Cloud-to-ground flash activity for each wind cluster group.

Cluster	Flashes	Events	Percent flashes	Percent events	Percent flashes in hotspot	Hotspot flashes/event
1	35 586	19	5.4	5.9	2.5	44
2	64 531	59	9.9	18.4	12.0	69
3	130 141	67	19.9	20.9	21.6	110
4	78 066	38	12.0	11.9	11.8	106
5	87 082	41	13.3	12.9	11.8	98
6	91 213	54	14.0	16.9	20.4	128
7	168 216	42	25.7	13.2	20.0	162

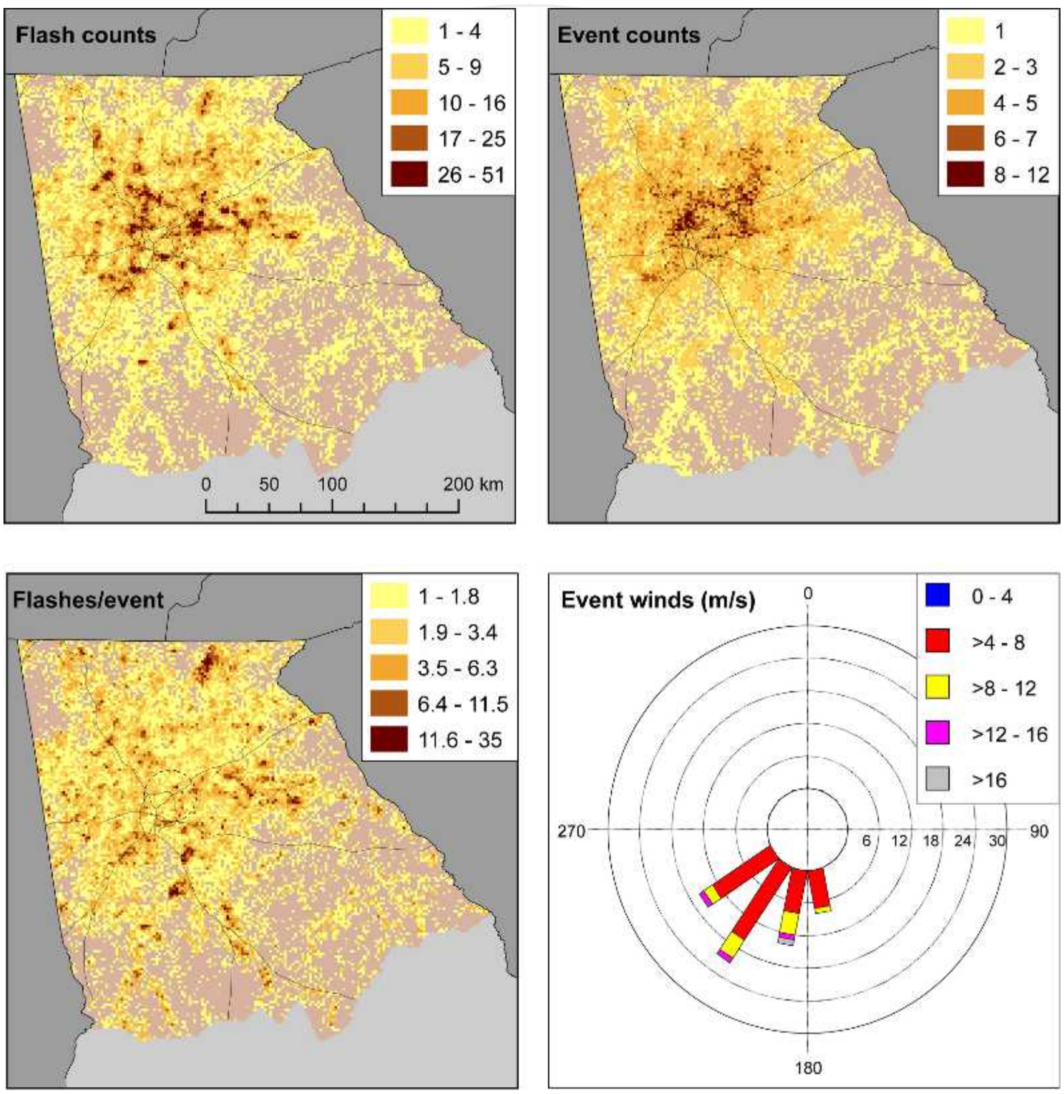

Figure 5. Flash metrics for cluster 2 (south-southwesterly 700-mb flow) and event wind rose.

(NARR 2007). The NARR project is an extension of the NCEP Global Reanalysis model applied only to North America (Mesinger et al. 2006). Accumulated precipitation was mapped as a daily mean value for all the dates flashes were observed within each of the seven wind clusters. Grid cell resolution is 32 km. Although the NARR precipitation data have some limits to their robustness (West et al. 2007; Bukovsky and Karoly 2007), they improve upon prior reanalysis datasets. To integrate lightning and precipitation visualizations, NARR graphical output was georectified in ArcGIS. For each wind cluster, the first five flashes of its constituent events were plotted. Polygons representing the general outline of peak flash production were also superimposed on top of precipitation contours.

Because individual flash event duration did not consistently correspond to the 3-h breaks upon which the NARR output is structured, we did not attempt to match

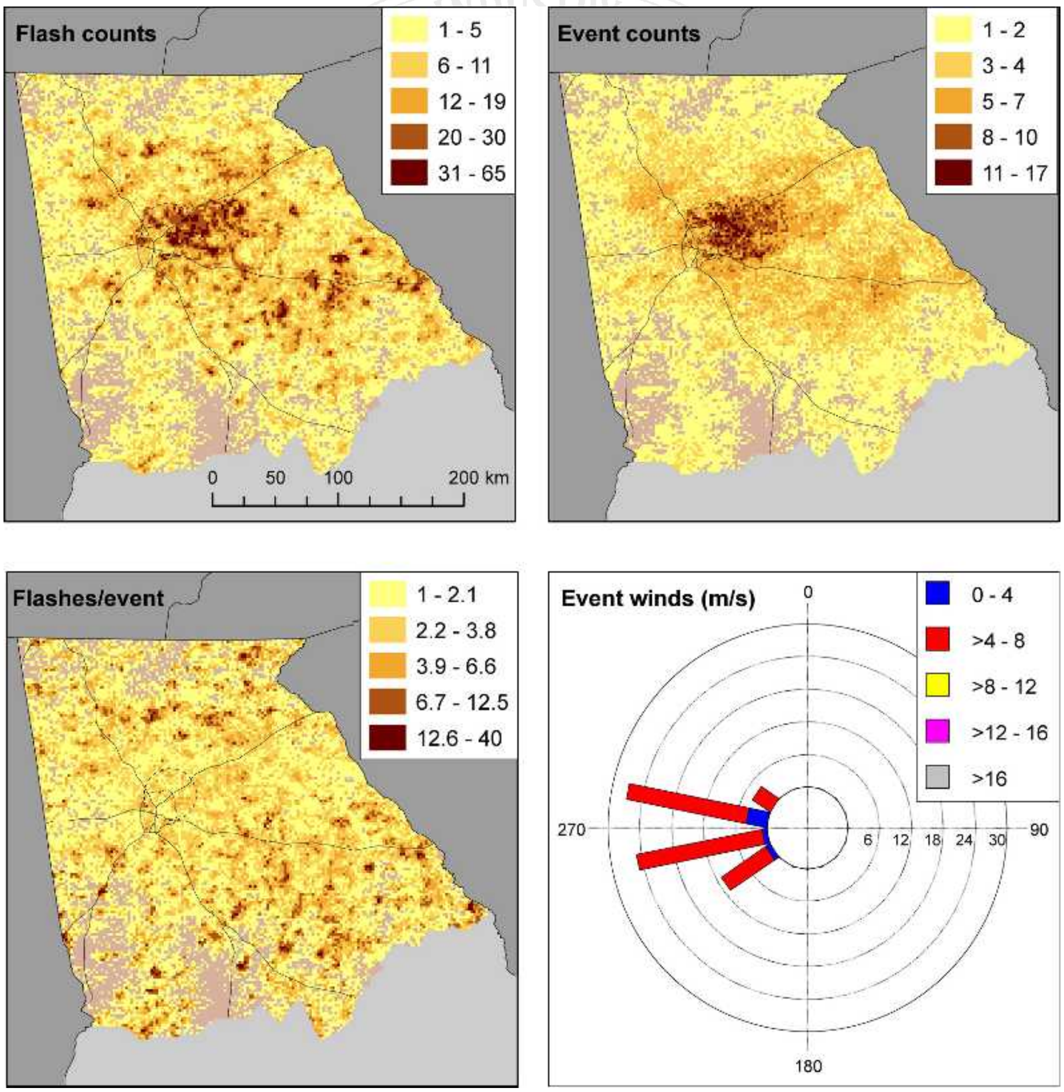

Figure 6. Flash metrics for cluster 3 (westerly flow 700-mb flow) and event wind rose.

Fig. 6 live 4/C

flashes in individual events with mean accumulated precipitation. Moreover, precipitation enhancement does not mean a surplus of precipitation. Relative differences in accumulated precipitation between upwind and downwind can be consistent with drought conditions.

5. Results

5.1. Flash patterns for wind clusters

The majority of flash events occurred on days with 700-mb flow from the west (Figure 3). Most of the flashes occurred within cluster 3 (westerly flow) and cluster 7 (northwesterly flow). Cluster 7 had a high number of flashes per event and more of these flashes fell within the northeastern hotspot compared to other clusters.

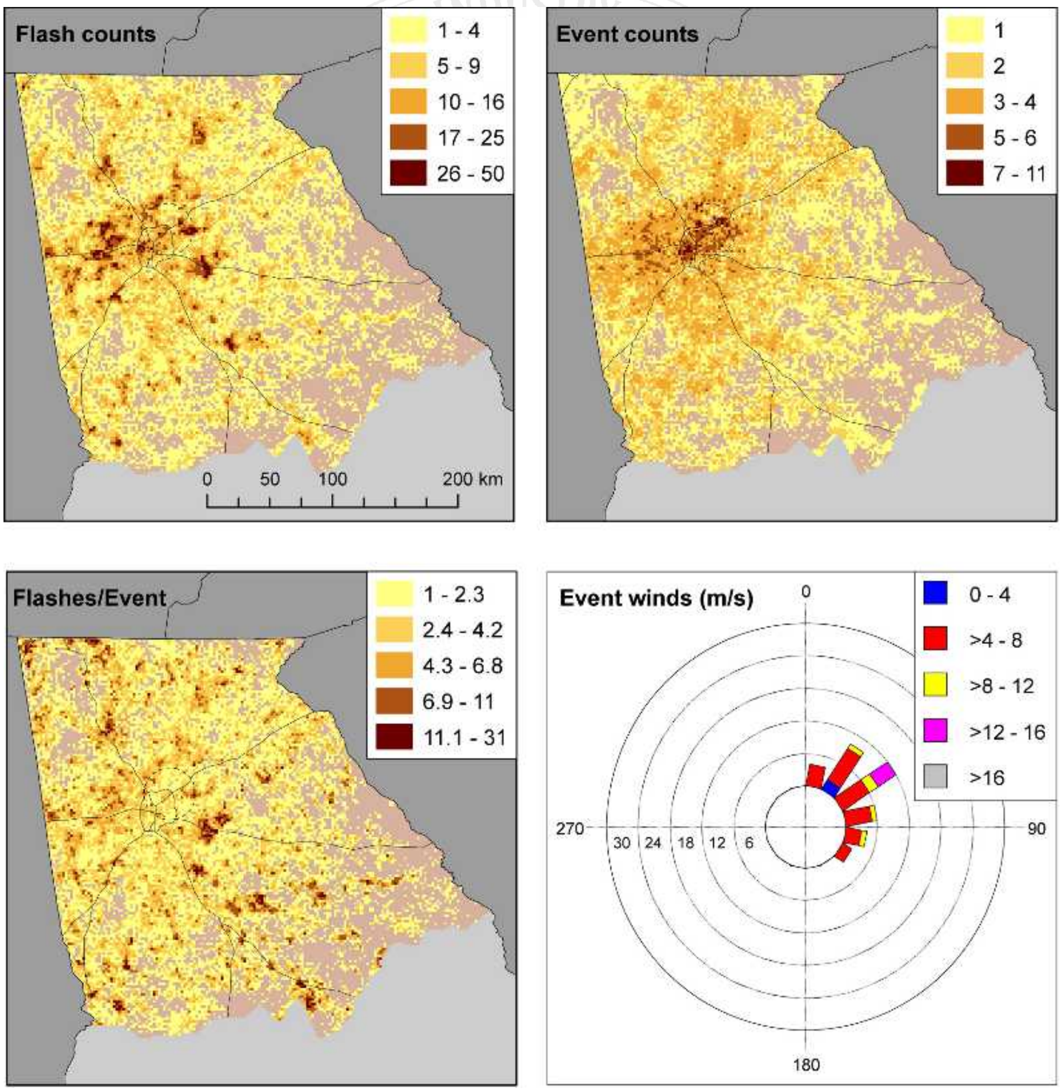

Figure 7. Flash metrics for cluster 4 (northeasterly 700-mb flow) and event wind rose.

Cluster 3 was distinctive for its high number of events even though it had fewer flashes than cluster 7.

Cluster 1 events had high relative wind speeds originating from the west. There were no discernible peaks in flash production (Figure 4). However, this cluster had only 19 flash events (Table 2). Cluster 2 events originated from the southwest under moderate wind speeds. Flash and flash event counts did not peak until downwind of the city (Figure 5). There was a propensity for flashes to bifurcate around the city along two trajectories. Cluster 3 events had slightly lower wind speeds than cluster 2 and a more westerly bearing. Downwind enhancement was also well developed (Figure 6). Flashes were reduced in the upwind region, and higher flash production did not develop until east of the city and downwind from the north–south-trending Interstate 75.

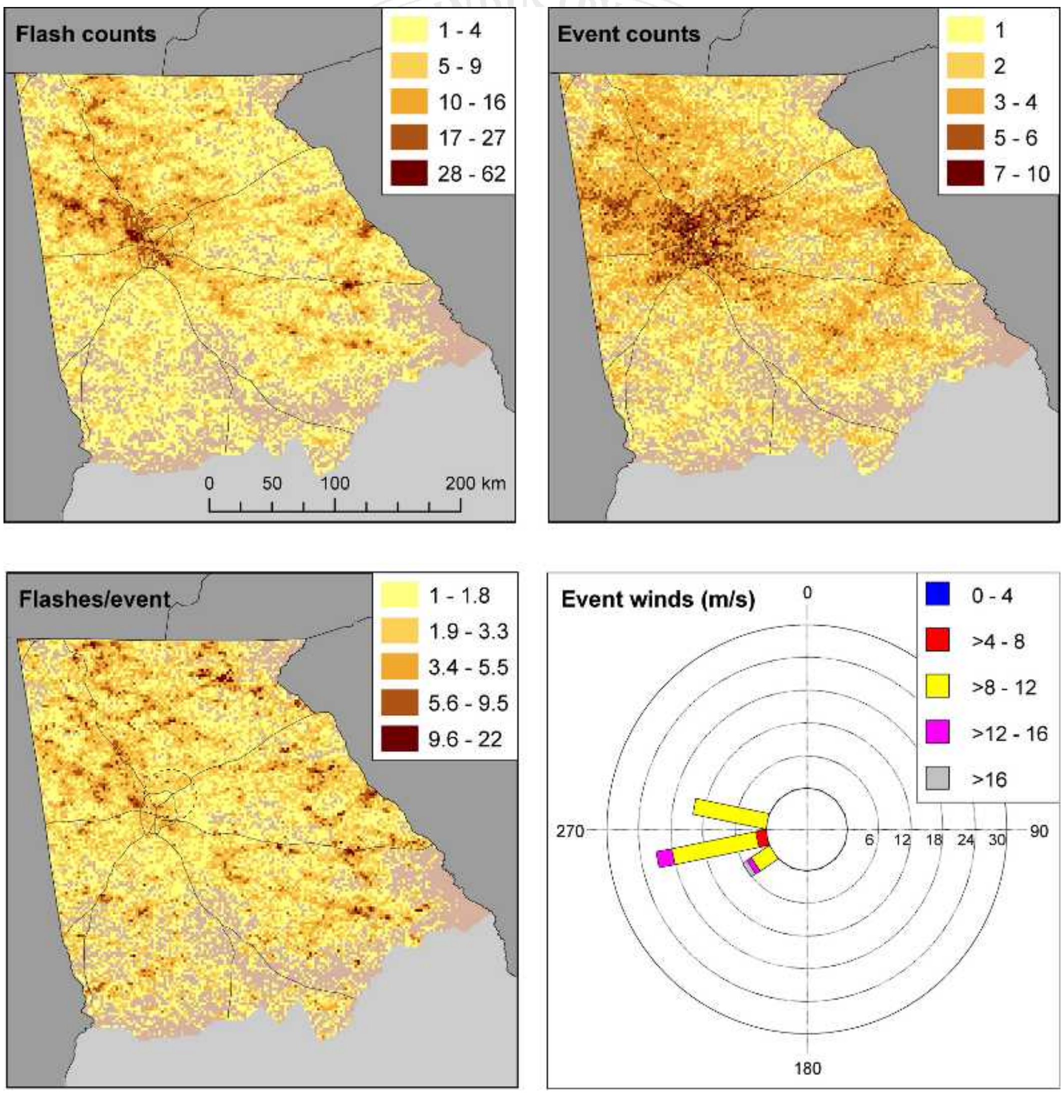

Figure 8. Flash metrics for cluster 5 (westerly 700-mb flow) and event wind rose.

Cluster 4 events originated from the northeast (Figure 7). Although flash enhancement was not originally anticipated from this direction, flash counts and flash events peaked in the downwind, west-southwesterly quadrant of the city. Cluster 5 events (Figure 8) produced more flashes and higher flash event counts over and *upwind* from the central city. Higher flash production did not extend downwind. Cluster 6 was comprised of events with low wind speeds (Figure 9). Low wind speeds are variable in direction because of instrumentation constraints. Peaks in flash counts were associated with surface features corresponding to the central city and south to Atlanta's international airport, the I-285 and I-75 node of urban development in the northwest and low-density sprawl in the northeast.

Cluster 7 events, defined by flow from the northwest at moderate wind speeds, produced more flashes downwind from the city (Figure 10). Flash activity was

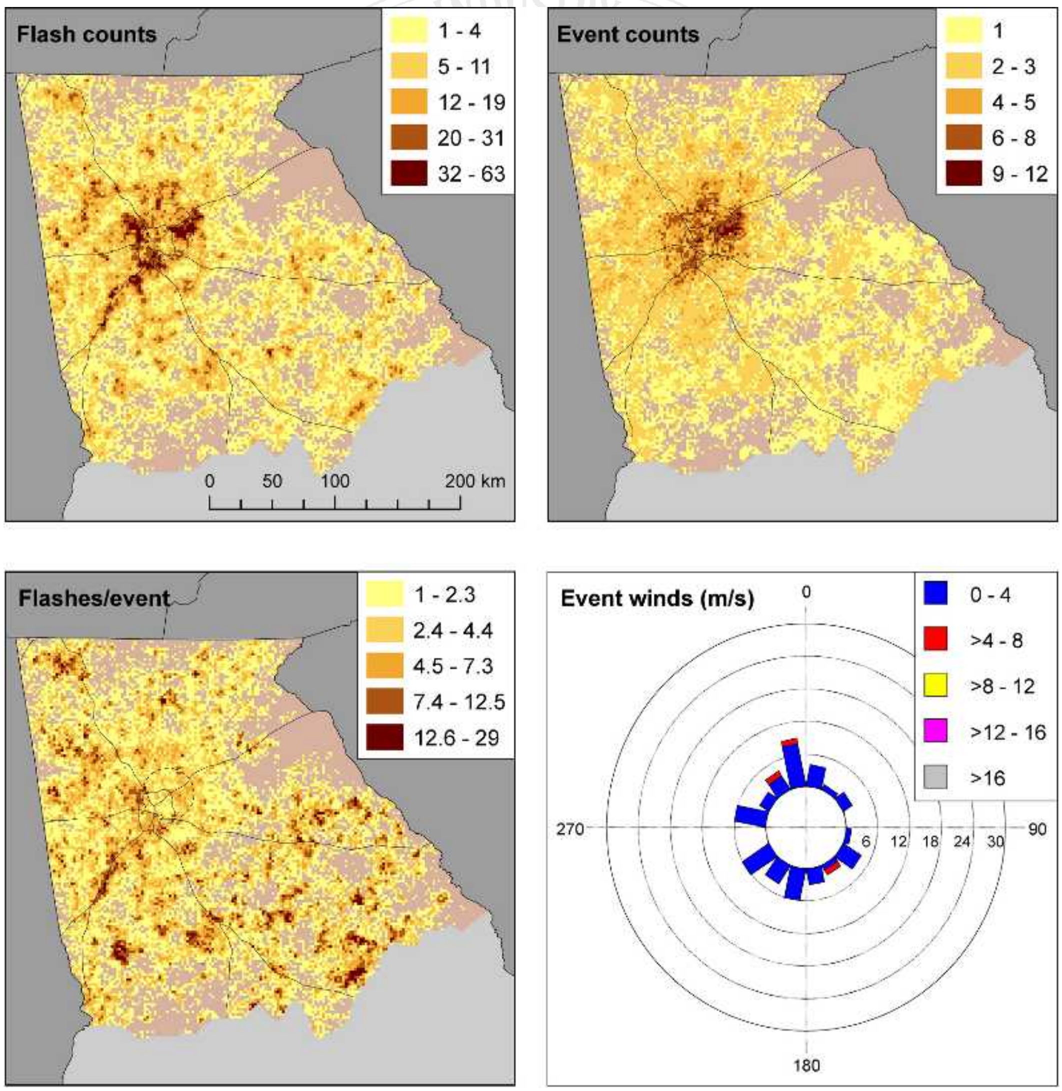

Figure 9. Flash metrics for cluster 6 (calm winds) and event wind rose.

diminished upwind. Clusters 3 and 7 illustrated that, as wind speeds increase, the location of downwind convection moves outward from the city center (Baik et al. 2001). Clusters 3 and 7 had northwesterly midlevel steering winds, but the location of maximum flash production for the slower wind speeds in cluster 3 was closer to the city center. The higher wind speeds in cluster 7 had a much longer downwind dispersion of flashes. These flashes extended southeast from the city over distances of approximately 75 km. High flash counts first emerged east of the city and along the north–south interstate running through downtown Atlanta.

5.2. Flash and precipitation patterns for wind clusters

Overlays of precipitation with polygons designating the location of peak flash production affirmed a geographically consistent coupling of precipitation and CG

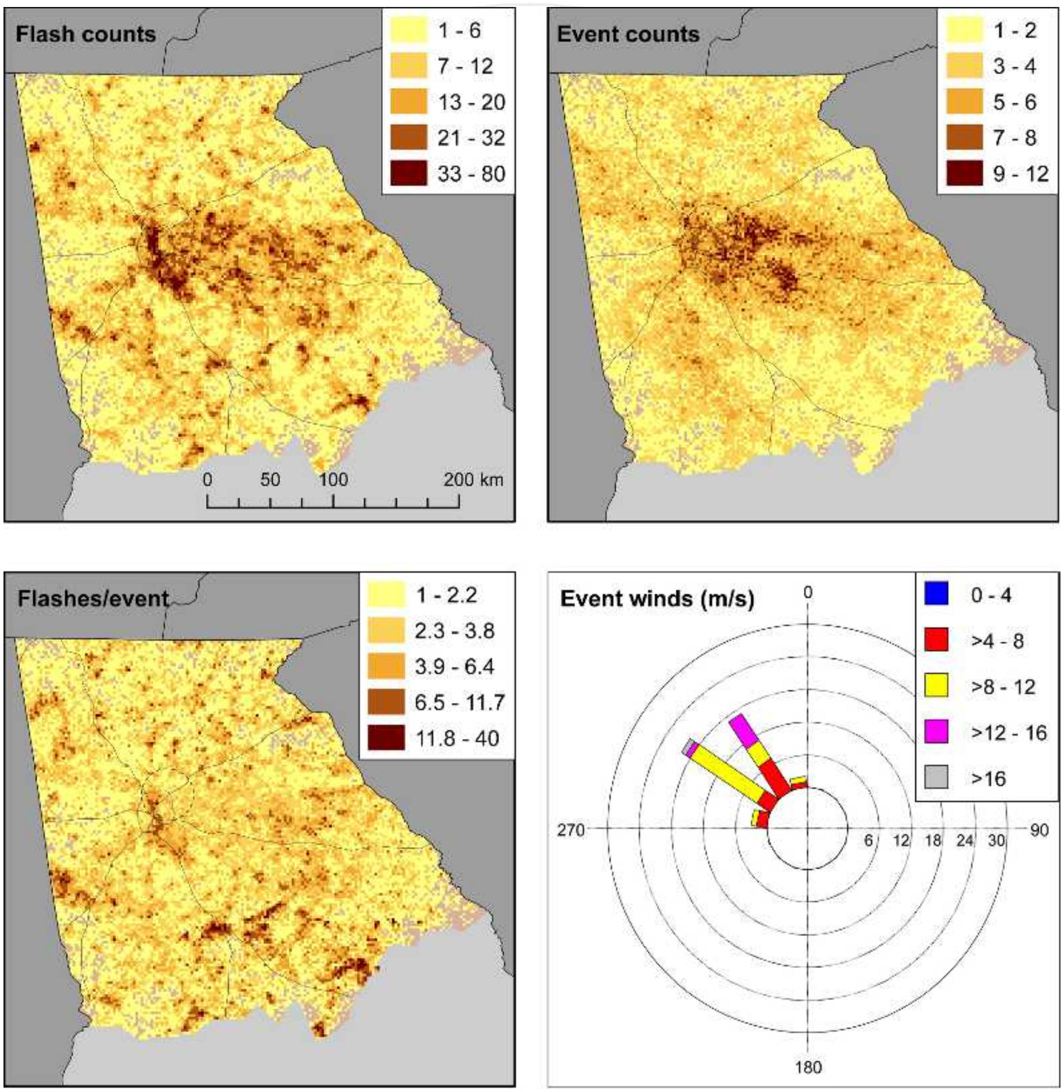

Figure 10. Flash metrics for cluster 7 (northwesterly 700-mb flow) and event wind rose.

Fig. 10 live 4/C

lightning enhancement around Atlanta. Flash and precipitation coassociation were indistinct for cluster 1 given its low number of events (Figure 11). Southwesterly flow in cluster 2 produced a node of higher mean accumulated precipitation on the downwind (northeast) side of Atlanta (Figure 12). This precipitation maximum is an extension of rainfall that reaches up from the Gulf Coast into central Georgia, only to disappear and then reemerge on the downwind side of Atlanta. Flashes initiated before the precipitation maximum, but a group of events also began flash production only upon entering the Atlanta urban area. Westerly flow in cluster 3 also produced a maximum in mean daily precipitation on the downwind side of Atlanta (Figure 13). Flash initiation was upwind of the urban area. The high flash production polygon is downwind and coincident with the precipitation maximum. A second precipitation maximum develops farther downwind and may be associated with Piedmont fronts (Businger et al. 1991). These areas of instability are caused by the convergence of outflow from sea-breeze thunderstorms with a mild elevational break along Georgia's fall line. The fall line is located along the southernmost border of our study area in Figure 2.

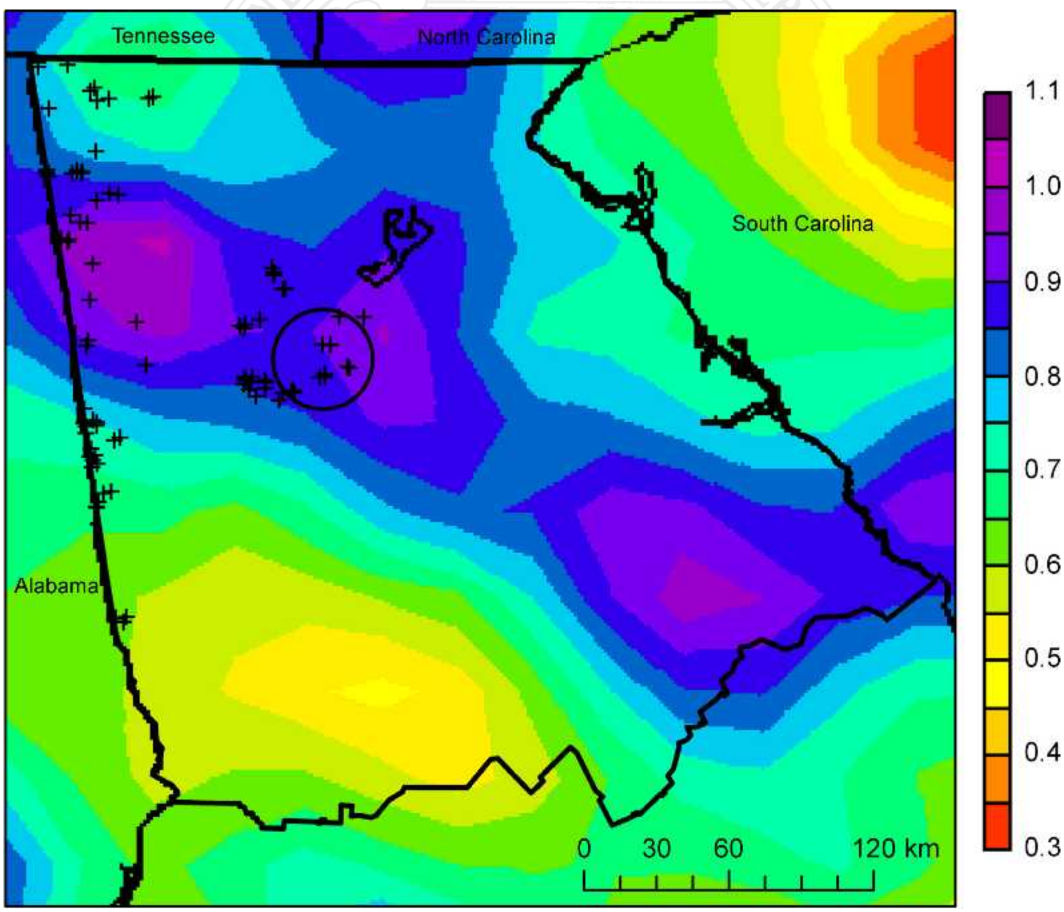

Figure 11. Mean accumulated precipitation for flash days in cluster 1 (west-northwesterly 700-mb flow). Point pattern represents first five flashes of each individual event in this cluster.

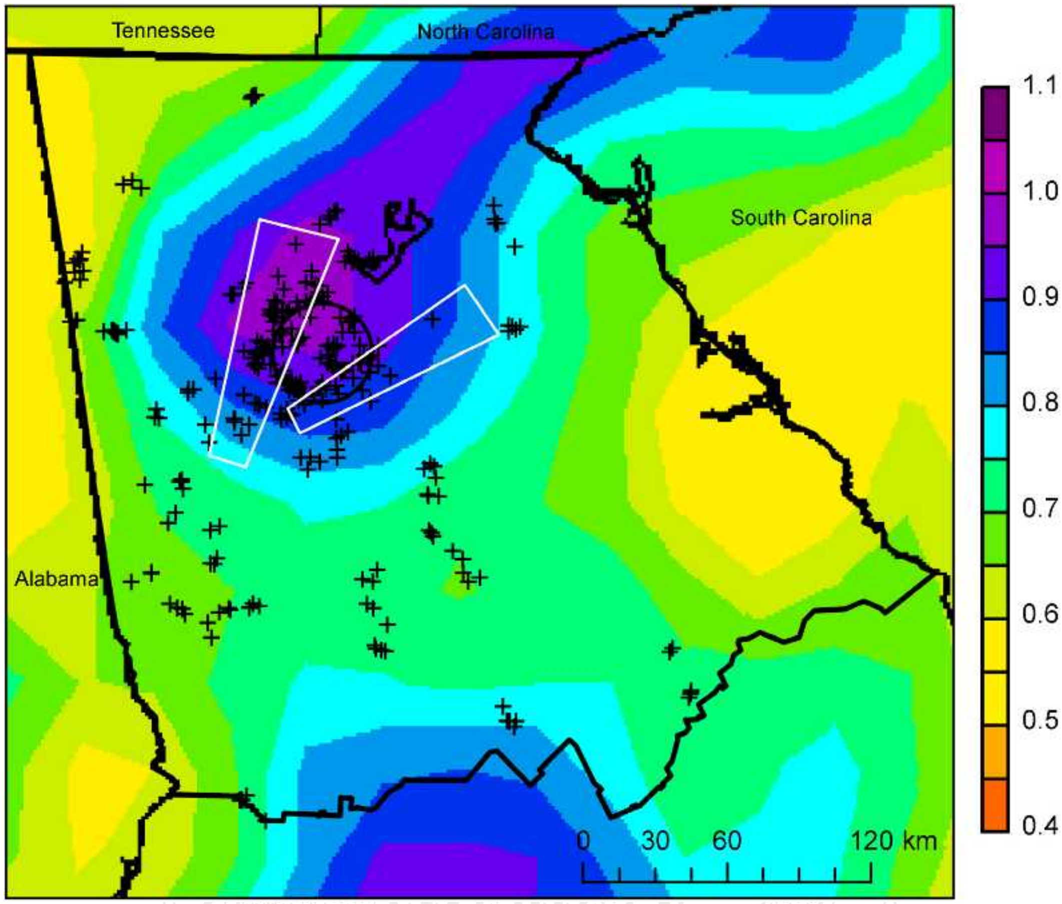

Figure 12. Mean accumulated precipitation for flash days in cluster 2 (south-south-westerly 700-mb flow). Point pattern represents first five flashes of each individual event in this cluster. Polygons are areas of high flash counts as based on Figure 5.

For the northeasterly flow events comprising cluster 4, a lobe of precipitation expands into Atlanta from precipitation activity in the southern half of the state (Figure 14). Flashes initiate upwind of the city, and then decrease before resuming around the northeast corridor of Atlanta, well upwind of the polygons representing the areas of higher flash production. A more westerly flow in cluster 5 (Figure 15) is also associated with greater precipitation in the Atlanta area. However, as with this cluster's flash maxima, rainfall is concentrated on the *upwind* side of Atlanta. This precipitation maximum is a southward extension of precipitation occurring in the Tennessee Valley. Some flash events for cluster 5 are active upon entering the state, as evidenced in the line of initial flashes along the Alabama–Georgia border. Initiation for other events is more tightly associated with the city. The low wind speeds and variable wind directions of cluster 6 (Figure 16) are associated with a broad area of light precipitation across the northern half of Georgia. A region of slightly higher precipitation develops southeast of Atlanta. Northwesterly flow in

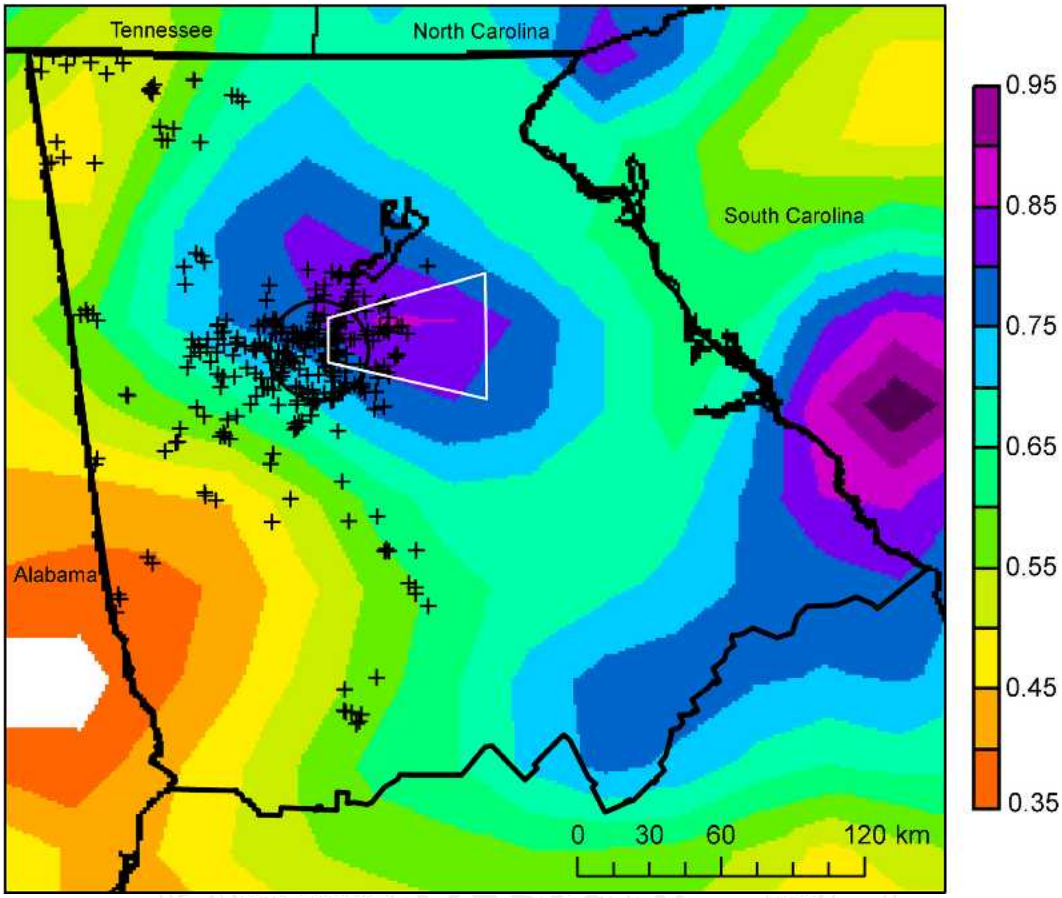

Figure 13. Mean accumulated precipitation for flash days in cluster 3 (westerly flow 700-mb flow). Point pattern represents first five flashes of each individual event in this cluster. Polygons are areas of high flash counts as based on Figure 6.

cluster 7 (Figure 17) also triggered increased precipitation across the Atlanta region. Precipitation maxima developed on either side of the city. Event flashes were either underway upon entering the state or initiated along the northeast edge of the city.

5.3. Flash patterns for individual events

Evidence for urban enhancement in individual storms was muted. Most individual events had flashes that were widely dispersed, with no discernible clustering of production around urban land cover. Moreover, the natural cycling of thunderstorm convection may override or obscure flash activity initiated or rejuvenated in the vicinity of an urban area. A small number of the 320 individual flash events, approximately 10%, conveyed evidence of urban influences. Most of the individual events having evidence for urban enhancement belonged to clusters 3 and 7.

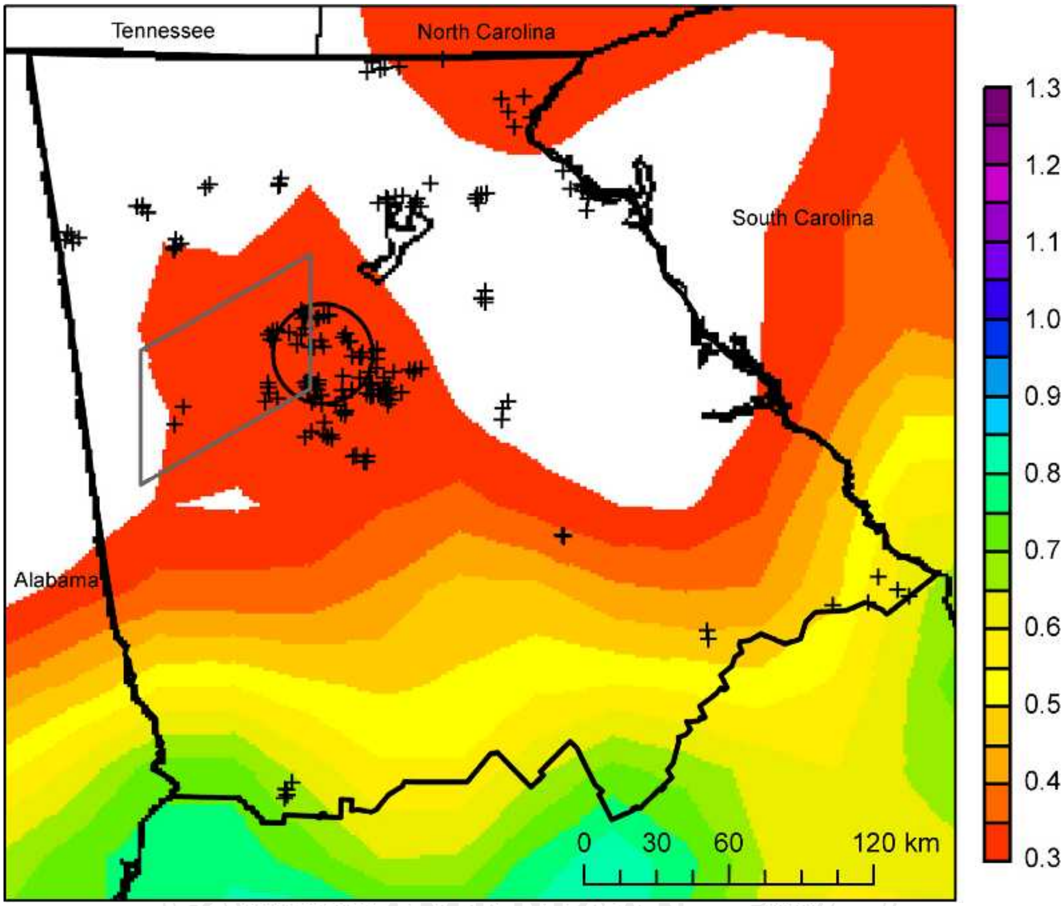

Figure 14. Mean accumulated precipitation for flash days in cluster 4 (northeasterly 700-mb flow). Point pattern represents first five flashes of each individual event in this cluster. Polygons are areas of high flash counts as based on Figure 7.

Several events followed a roughly linear path parallel to the wind direction and had flash peaks upwind or just downwind from the city center (Figure 18). These flash events were also isolated, with few to no flashes developing elsewhere across the northern half of Georgia. Correspondence effects were observed, most prominently in two flash events that tracked along interstate highways (Figure 19). Rejuvenation of flash production either in or downwind from the central city was also detected (Figure 20). A small set of individual flash events had a narrow focal point of flash initiation around Atlanta, and a divergence outward in flashes in the downwind direction (Figure 21).

6. Discussion

Precipitation and flash enhancement were observed at multiple downwind positions around Atlanta. As steering wind direction changed, so did maxima in

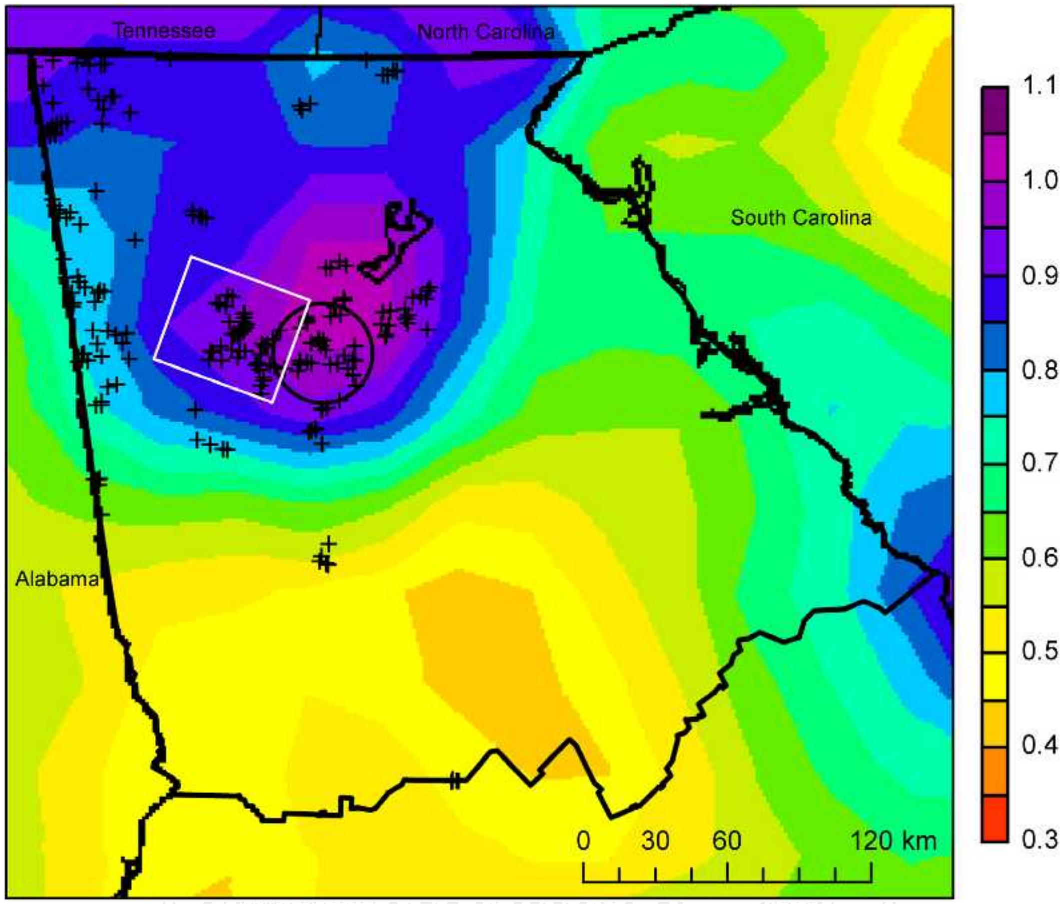

Figure 15. Mean accumulated precipitation for flash days in cluster 5 (westerly 700-mb flow). Point pattern represents first five flashes of each individual event in this cluster. Polygons are areas of high flash counts based on Figure 8.

precipitation and flashes. Enhancement effects, particularly for cloud-to-ground lightning, were well developed for westerly and northwesterly wind flow. Our finding that flash and precipitation enhancement occurs at all directions around Atlanta supports earlier studies that found locations all around the city center as urban anomalies in precipitation, lightning, and convection. Hand and Shepherd (Hand and Shepherd 2008) found similar precipitation anomaly mobility around Oklahoma City. Although enhancement effects were best developed under westerly and northwesterly midlevel winds, flow from off the Appalachians to the northeast was also associated with an area of increased rainfall and precipitation. More information about the local wind in each cluster is needed to clarify surface thermodynamic mechanisms.

Differences in the patterns of flash metrics (flash counts versus event counts), the absence of any strong urban signal in the flashes of individual thunderstorms,

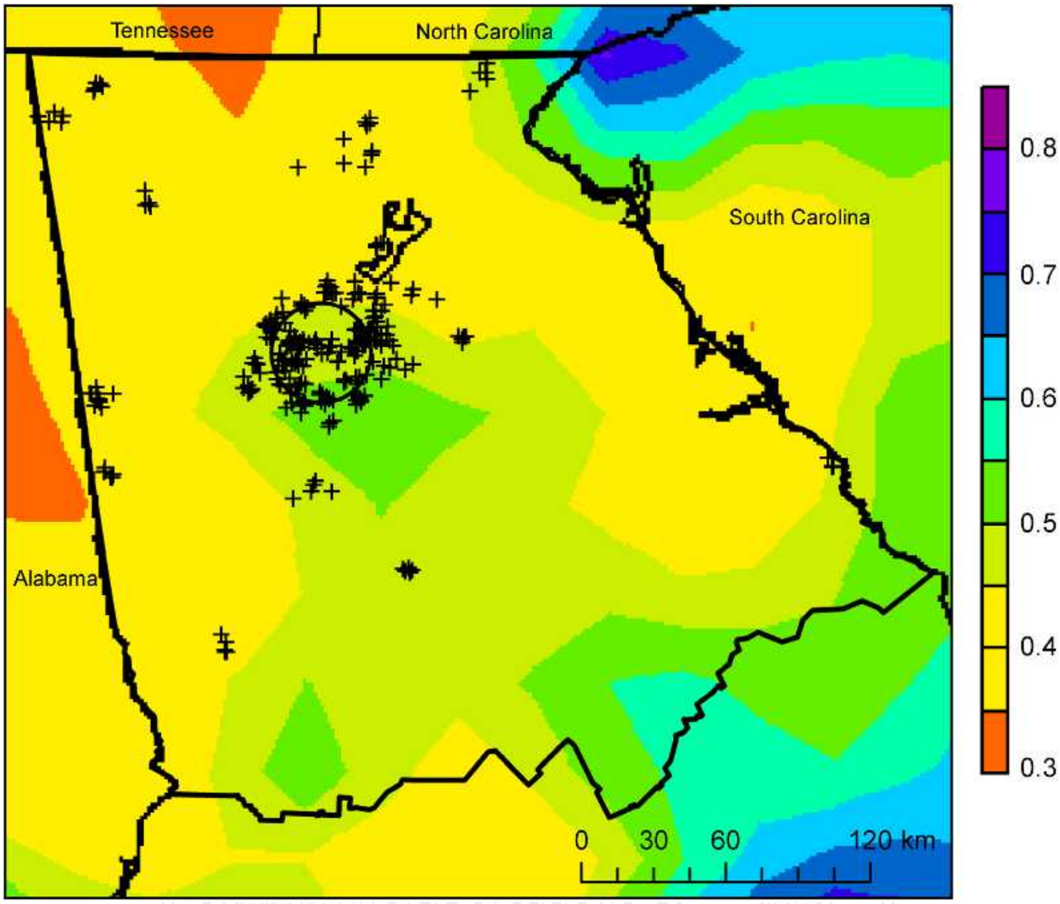

Figure 16. Mean accumulated precipitation for flash days in cluster 6 (calm winds). Point pattern represents first five flashes of each individual event in this cluster. Polygons are areas of high flash counts as based on Figure 9.

and the scales over which flashes and precipitation enhancement developed suggest how land-cover and aerosol mechanisms of urban weather modification differ. Total flash counts were less smoothly demarcated when compared to the number of flash events (Figures 4–10). Flash counts may be noisier because of the variable nature of aerosol sizes and concentrations, and their impacts on collision–coalescence processes. Subsequently, the number and patterns of flash event counts may be a more direct expression of urban land cover on local atmospheric thermodynamics. This may in part explain why it was difficult to detect anthropogenic enhancement in individual storms. At the smaller spatial and temporal extents of individual events, the relatively static influence of land cover may contribute to the initiation of convection and the overall propensity for flashes to develop, but the actual number of flashes may depend upon the particulars of aerosols and other atmospheric properties on that day and time.

Although muted, the regional physiography may also be linked to the observed flash and precipitation patterns (see Thielen and Gadian 1996; Thielen et al. 2000).

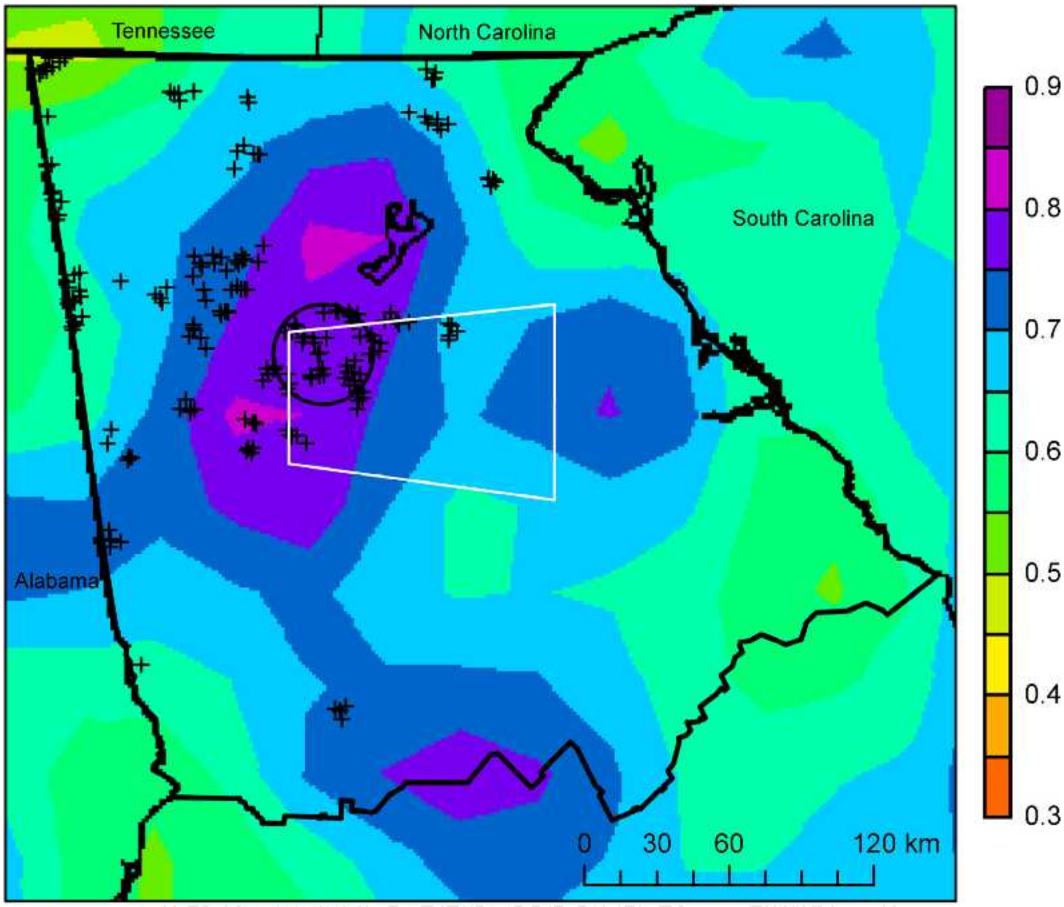

Figure 17. Mean accumulated precipitation for flash days in cluster 7 (northwesterly 700-mb flow). Point pattern represents first five flashes of each individual event in this cluster. Polygons are areas of high flash counts as based on Figure 10.

Flow from off the Appalachians in cluster 4 and the confinement of precipitation and flash maxima to the upwind side of Atlanta in cluster 5 suggest that the configuration of elevations across the region may interact with urban circulations. These local-to-regional interactions among land cover, aerosols, and physiography suggest that the untangling and articulation of the scale domains of these variables remains the greatest challenge to understanding how urban regions influence their weather. In particular, given that aerosol characteristics can change across time and space rapidly, there is no reason to assume that a single city should exhibit consistently enhanced flash and precipitation production across all scales. Complex multimodal distributions of aerosol sizes and compositions, superimposed onto background aerosols from biological sources (Mohler et al. 2007) or from maritime influences (Rosenfeld et al. 2002), should introduce much more city-to-city variability and historical contingency (due to dust-producing droughts or intensive land-use conversion) in the patterns of urban weather modification.

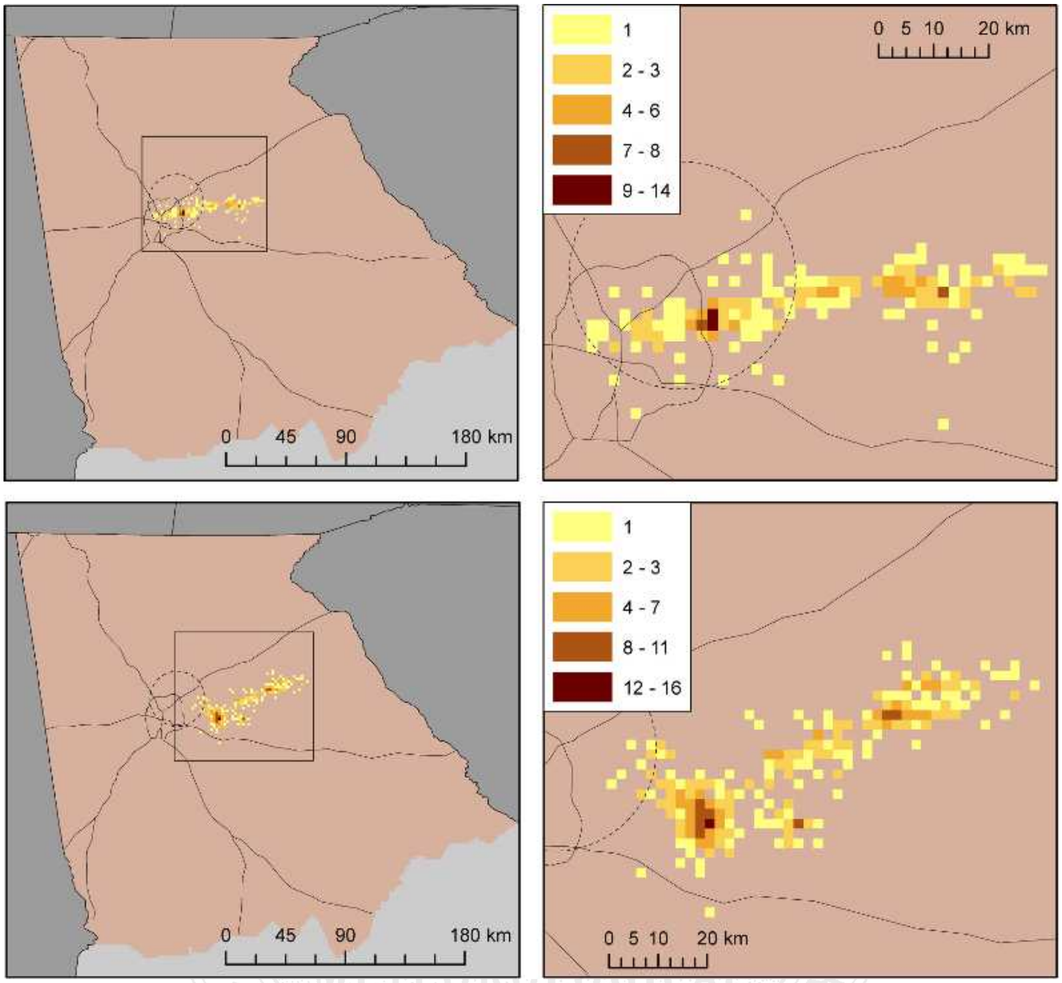

Figure 18. Candidate urban flash enhancement events having isolated, linear flash production downwind of Atlanta. (top) Flash event on 17–18 Aug 2002 between 2210 and 0049 local standard time (LST) under westerly flow associated with cluster 3. (bottom) Flash event from 19 Jun 2000 between 1646 and 1933 LST under westerly flow in cluster 3.

7. Summary

For the warm-season airmass-dominated flash days selected through an adaptive sampling design, maxima in precipitation and cloud-to-ground lightning developed under several different midlevel wind direction and speed combinations. Overlays of precipitation and flash metrics affirmed a geographically consistent precipitation and CG lightning enhancement around Atlanta. Maxima in mean daily accumulated precipitation shifted in response to changes in wind direction in a manner similar to flashes. The distribution of initial thunderstorm flashes at locations well away from Atlanta or along the city's upwind edge suggests that proximity to Atlanta reinvigorates the conditions necessary for flash production. By contrast,

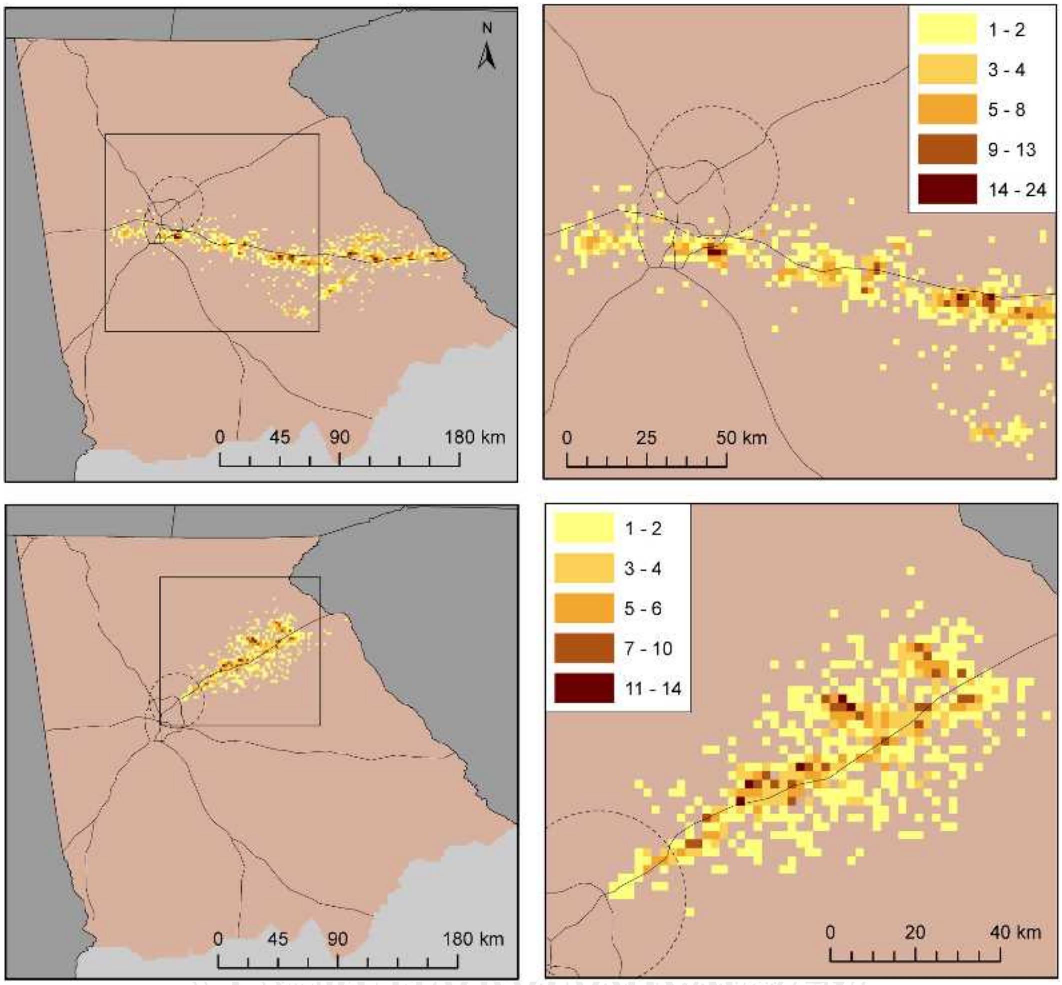

Figure 19. Candidate urban flash enhancement events having correspondence with underlying anthropogenic features (interstates). (top) Flash event on 14–15 Aug 1997 between 1941 and 0010 LST under westerly flow associated with cluster 5. (bottom) Flash event from 21–22 Jun 2003 between 2115 and 0024 LST under westerly flow in cluster 3.

precipitation maxima had varying degrees of isolation, but were often expressed as discontinuous lobes extending from adjacent areas of widespread precipitation.

To elucidate how aerosol effects are expressed, more detail about the timing of precipitation with lightning is required. In Atlanta, can finer-diameter aerosols delay precipitation such that thunderstorms have a longer period of flash activity before enhanced rainfall develops? In other words, are there relatively dry thunderstorms over some areas of the city? Do coarser aerosol diameters initiate rainfall sooner, but produce fewer flashes? Are there precipitation suppression events (see Kaufmann et al. 2007)? Rosenfeld and Givati (Rosenfeld and Givati 2006) and Rosenfeld et al. (Rosenfeld et al. 2007a) observed decreased precipi-

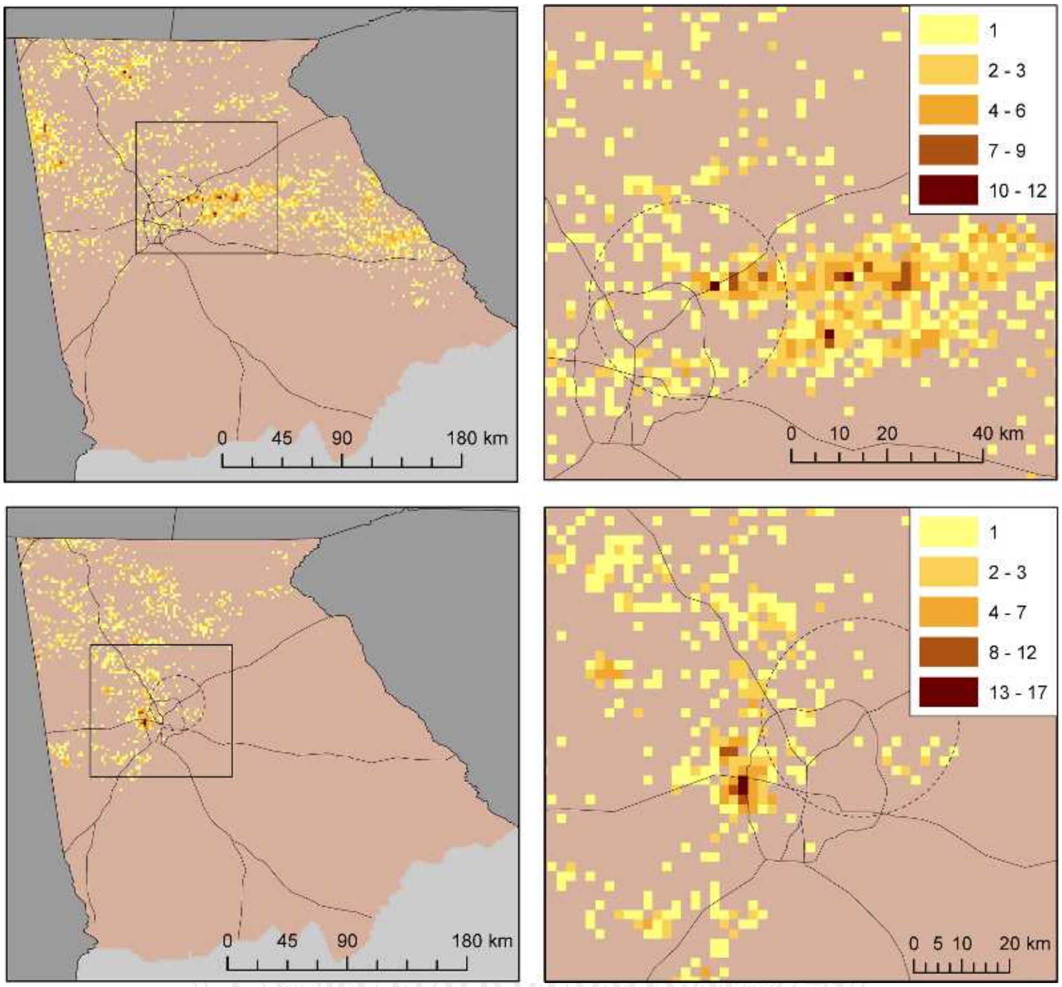

Figure 20. Candidate urban flash enhancement events having rejuvenation in the vicinity of urban land uses. (top) Flash event from 14 Sep 1995 between 0955 and 1712 LST under northwesterly flow associated with cluster 7. (bottom) Flash event from 4–5 Jul 2001 between 2253 and 0326 LST under northwesterly flow in cluster 7.

tation at large distances downwind of cities (where underlying land-cover properties are absent) in association with submicron-sized aerosols, diameters well below the typical PM10–PM2.5-μm sizes found to correlated with urban flashes (Steiger and Orville 2003; Naccarato et al. 2003). In light of the sensitivity of cloud-formation processes to aerosols, city-specific studies that can integrate explicitly spatial data about aerosol size (de Almeida Castanho et al. 2008) will be better able to extract the full range of suppression and enhancement effects.

Future studies may find it useful to conduct multivariate clustering of a suite of independent variables. For example, rather than using only wind clusters to structure visualizations of precipitation and lightning, days with different aerosol distributions could be used to stratify observations. To complement flash- and event-

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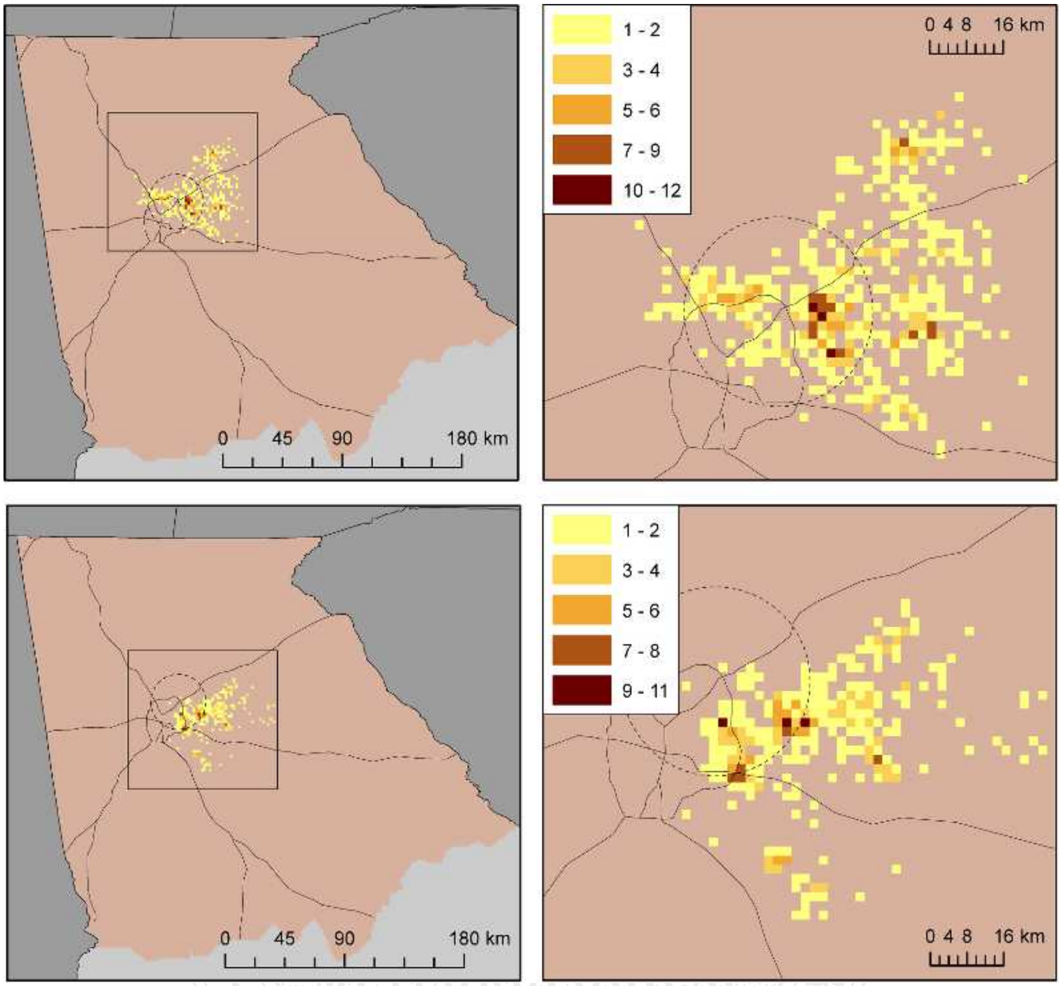

Figure 21. Candidate urban flash enhancement events having a narrow locus of flash initiation around Atlanta, and a divergence outward in flashes in the downwind direction. (top) Flash event from 6–7 Jun 2002 between 2044 and 0028 LST under westerly flow associated with cluster 3. (bottom) Flash event from 1–2 May 2003 between 2244 and 0221 LST under westerly flow in cluster 3.

count-based indicators of urban weather modification, the percentage of positive flashes, a metric shown to be sensitive to urban aerosols, could also be employed. Multicity comparisons spanning a range of climates would provide insight into how background aerosol loads interact with urban influences (Van Den Heever and Cotton 2007). Although flash events with weak synoptic forcing were examined in our study, strongly forced convection may also be affected by the urban environment (Niyogi et al. 2006). Other causal factors to consider include cloud-base heights, cloud vertical development, precipitation rates and reflectivities, all interrelated parameters that can reveal more about how urban areas influence convection (Gauthier et al. 2005; Lensky and Drori 2007; Freud et al. 2008).

Fig. 21 live 4/C

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