

## Short Communication

# Synoptic environments favourable for urban convection in Atlanta, Georgia

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**ABSTRACT:** An examination of synoptic environments conducive to urban thunderstorm development surrounding Atlanta, Georgia, was conducted. Synoptic environmental characteristics were evaluated utilising regional analyses of heights, winds, temperature, and moisture characteristics as well as several thermodynamic variables. A flexible beta cluster analysis was used in order to identify disparate groupings of common synoptic and thermodynamic environments. These groupings were then further analysed through the production of synoptic composites, radar, and lightning distributions. Although the analysis stratified the data by days with weak synoptic flow and maritime tropical airmass characteristics, enough variation existed within the synoptic and thermodynamically grouped parameters to identify four distinct environments present during urban thunderstorms. Environments exhibiting moderate thermodynamic instability were found to produce the highest flash rates and most frequent composite reflectivity days. Copyright © 2011 Royal Meteorological Society

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## 1. Introduction

Evidence suggests the effects of urban areas on the regional atmospheric environment goes beyond the urban heat island (UHI) to encompass precipitation and convective processes (Shepherd, 2005; Stallins and Rose, 2008; Shepherd, 2010). The impact of heating due to urbanisation destabilizes the boundary layer, strengthens thermal circulations, and can trigger deep, moist convection (Dixon and Mote, 2005; Shepherd and Burian, 2003; Shepherd, 2005). Aerosols emanating from urban pollution can also modify the collision-coalescence process leading to differing precipitation rates and intensity (Rosenfeld *et al.*, 2008). The urban core, as well as the downwind periphery, are two regions especially susceptible to urban-enhanced thunderstorms (Niyogi *et al.*, 2006; Shem and Shepherd, 2009).

As urbanisation continues to increase worldwide, its interaction regionally and locally with anthropogenic climate modification provide strong impetus for further investigation (Elvidge *et al.*, 2004). In addition, increases in population density within urban areas leads to elevated vulnerabilities to thunderstorm hazards such as lightning, downbursts (and microbursts), urban flooding, and hail.

This investigation examines regional environments of warm-season (June through August) thunderstorm activity surrounding Atlanta, Georgia, 1997–2006. Our primary objective is to characterize environments conducive to thunderstorm development during warm-season, synoptically benign days when the effects of the Atlanta UHI on modulating convective activity is maximized. The research examines 244 days when thunderstorms developed within 80 km of Atlanta. The thermodynamic variables were used to group days with similar environments and the groupings were then composited in order to determine regional synoptic meteorological characteristics.

## 2. Background

Research into the distribution of urban thunderstorms has focused on large urban areas such as Houston, Atlanta, Phoenix, and New York (Balling and Brazel, 1987; Bornstein and LeRoy, 1990; Selover, 1997; Orville *et al.*, 2001). More recently, remote sensing platforms such as the National Weather Service (NWS) WSR-88D network of radars have been used to develop thunderstorm climatologies and investigations into precipitation cycles (Ahijevych *et al.*, 2003; Parker and Knivel, 2005; Mote *et al.*, 2007; Ntelekos *et al.*, 2007).

Atlanta, GA, experiences frequent weakly forced thunderstorm convection during the warm season (Bentley

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*et al.*, 2010). Results from a Georgia lightning climatology found that over half of all reported flashes emanated from warm-season, air-mass storms (Bentley and Stallins, 2005). Evidence illustrates that thunderstorms developing during periods of weak synoptic forcing are sensitive to urbanisation effects as lightning and radar reflectivity hotspots surrounding Atlanta were found to be more tightly coupled to the outline of the central city and outlying hubs of high-density development (Stallins and Bentley, 2006; Bentley *et al.*, 2010). Therefore, this investigation will focus on the environments of warm-season (June through August), air mass convective storms, 1997–2006.

### 3. Data and methods

Our analyses utilized a radar climatology developed for Atlanta incorporating NOWrad national composites of WSR-88D reflectivity data (Bentley *et al.*, 2010). The NOWrad national composite is a gridded dataset available in 5-min, 2 km × 2 km, temporal and spatial resolution respectively. After stratifying the NOWrad dataset by warm-season months (June, July, August), a spatial synoptic classification (SSC) was employed to identify synoptically benign, convectively unstable days (Bentley *et al.*, 2010; S. C. Sheridan, Spatial synoptic classification data, <http://sheridan.geog.kent.edu/ssc.html>, 2007). SSC classifies seven different weather types, including transitional days between a specific air mass (Sheridan, 2002). We selected MT (moist tropical), MT+ (moist tropical plus) and MT++ (moist tropical plus-plus) days to analyse as these are when thunderstorms are most susceptible to urban effects (Dixon and Mote, 2005; Bentley *et al.*, 2010). After stratifying for the warm season and air mass, 415 days were identified to develop the radar climatology (Bentley *et al.*, 2010). A radar composite reflectivity of 40 dBZ is defined as a minimum for determination of a thunderstorm. This baseline reflectivity is commonly used as a discriminator between convective and stratiform events using composite reflectivity (Falconer, 1984; Rickenbach and Rutledge, 1998; Parker and Knivel, 2005). The number of days a 2 km × 2 km grid cell registered a composite reflectivity of 40 dBZ or greater surrounding Atlanta were 376 (Bentley *et al.*, 2010). These days include convection ranging from moderate to severe thunderstorms that have the potential to produce urban flooding, frequent lightning, and damaging microbursts and downbursts (Roberts and Wilson, 1989).

Upper air soundings for Peachtree City, GA, from the University of Wyoming's Department of Atmospheric Science's website were obtained for the 376 convective days in the dataset (<http://weather.uwyo.edu/upperair/sounding.html>, 2005). The daily 00 UTC sounding was chosen in order to sample the most unstable ambient environment for warm-season, air-mass thunderstorms surrounding Atlanta. The thermodynamic variables and indices selected from the sounding for analysis include the following: convective available potential energy

(CAPE), total-totals index, lifted index, K-index, mean mixed-layer potential temperature, mean mixed-layer mixing ratio, 1000–500 hPa layer-averaged thickness and precipitable water. These eight parameters were chosen in order to evaluate the amount of static stability present during the urban thunderstorm days (Bentley *et al.*, 2010). After deleting times with no or incomplete thermodynamic data, 244 days were left for the statistical analyses.

A flexible beta clustering method was employed to link similar groupings of the eight sounding parameters across the 244 days (Lance and Williams, 1966). Similarity distances for cluster groups were expressed as Sorenson's distances. The flexible beta method allows users to specify a beta value ranging from −1 to 1. By choosing different beta values, the number of final cluster groups produced can be customized. As beta approaches 1, the number of cluster groups increases. As beta approaches −1, the number of groups decreases and each become larger in size. A beta of −0.5 was used in this analysis and yielded 10 groups from the 244 days of input-sounding parameters. After viewing a PCA scatterplot with individual dates coded by cluster groupings, four groups of days were chosen for synoptic composite analysis. These four groups span the scatterplot and contain the least amount of overlap among the eight parameters (Figure 1). It is expected that the selection of these four groupings of days will illustrate the spectrum of ambient environments associated with urban thunderstorm activity surrounding Atlanta.

Surface and upper-air data used to construct the composite analyses were obtained from NCEP's North American regional reanalysis, a long-term, consistent, high-resolution climate dataset that improves upon earlier global reanalysis datasets in both resolution (32 km) and accuracy (Mesinger *et al.*, 2006). Composites of daily mean sea level pressure, 2m temperature, dew-point, CAPE, planetary boundary layer depth, and winds were constructed for each of the four groups. In addition, upper-air composites consisting of temperature, geopotential height, specific humidity, and winds were constructed for 850, 700, 500, and 250 hPa. Finally, radar and lightning distributions were mapped for the four groups of convective days.

### 4. Results

The four groups identified from the cluster analysis comprise 109 of the 244 days used to determine the groupings (Table I). It is important to examine trends among several indices when determining atmospheric static stability, therefore, four were chosen for assessment. Surface-based convective available potential energy (CAPE) is the integration of positive area on a thermodynamic diagram. The positive area is that region where the theoretical parcel temperature is warmer than the actual temperature at each pressure level in the troposphere. The theoretical parcel temperature traces an ascent curve the unstable parcel

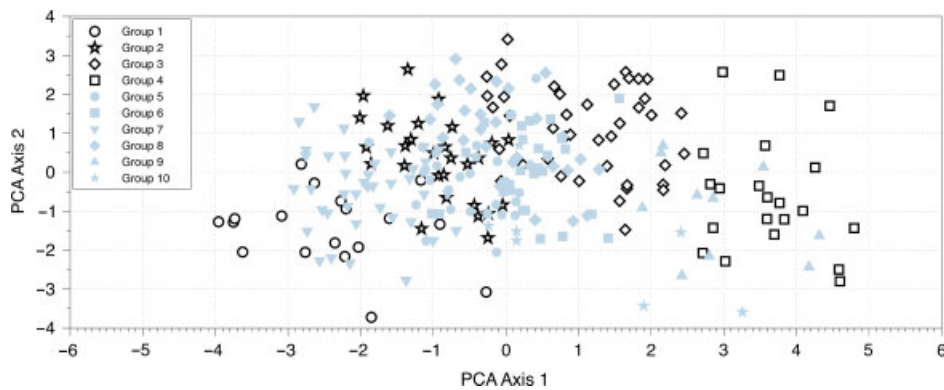


Figure 1. PCA scatterplot of analysis dataset. Symbols represent flexible beta clustering groups. Groups 1 through 4 were chosen for the analysis. This figure is available in colour online at [wileyonlinelibrary.com/journal/joc](http://wileyonlinelibrary.com/journal/joc)

Table I. Average values of thermodynamic indices, variables and daily flashes for the four groups. TT: total-totals index, LI: lifted index, KI: K-index.

Group	Day count	CAPE ( $\text{J kg}^{-1}$ )	TT ( $^{\circ}\text{C}$ )	LI ( $^{\circ}\text{C}$ )	KI ( $^{\circ}\text{C}$ )	Mean mixed layer potential temp. (K)	Mean mixed layer mixing ratio ( $\text{g kg}^{-1}$ )	1000–500 hPa layer thickness (gpm)	Precipitable water (mm)	Flashes per day
1	19	2679	49	-6	32	305	17	5768	43	3,429
2	28	1148	46	-3	35	303	16	5766	48	9,339
3	41	192	44	0	33	302	14	5764	45	8,378
4	21	65	42	1	20	305	11	5768	30	132

would follow with high parcel temperatures generating more CAPE and indicating greater convective instability (Moncrieff and Miller, 1976). The total-totals is an index used to assess thunderstorm strength. The index is calculated using both temperature and dew point at 850 hPa and the temperature at 500 hPa. An index greater than 40 generally indicates an environment conducive to thunderstorms, with values greater than 50 illustrating a potential for severe thunderstorms (Peppler, 1988). The lifted index assesses the low-level parcel instability. It is calculated by comparing an estimated parcel temperature at 500 hPa to the observed temperature. A negative lifted index indicates that the boundary layer is unstable in comparison to the mid-level atmospheric environment. The more negative the lifted index, the more unstable the troposphere and the greater the acceleration of rising parcels residing in the boundary layer (Peppler, 1988). The K-index assesses summertime air-mass thunderstorm potential using the 850 hPa temperature, dew point, 700 hPa dew point depression, and 500 hPa temperature (Peppler, 1988). The K-index incorporates a portion of the total-totals equation in addition to lower tropospheric moisture characteristics with the dew point depression believed to be an essential variable in assessing air-mass thunderstorms (Peppler, 1988). Generally, a K-index of greater than 26 indicates thunderstorm potential with values exceeding 40 indicative of widespread thunderstorms.

The greatest range in the thermodynamic indices were for CAPE and lifted index, ranging from  $2679 \text{ J kg}^{-1}$ ,

$-6^{\circ}\text{C}$  for group one, to  $61 \text{ J kg}^{-1}$ ,  $1^{\circ}\text{C}$ , for group four (Table I). Group one exhibits strong instability and a high potential of strong to severe thunderstorm development, and group four exhibits weak instability and a low potential of thunderstorm development. Groups one and two consistently register values of moderate to strong instability through all indices, while group one is the most unstable and group four the most stable among the thermodynamic indices examined (Table I). Overall static stability is more difficult to determine when examining group three as the K-index and total-totals indicate sufficient low-level moisture and instability for thunderstorm development; however, the lifted-index and CAPE are only marginally unstable (Table I). The other atmospheric variables examined show less group-to-group variation than the thermodynamic indices.

The radar climatology, generated from days when composite reflectivity was greater than 40 dBZ, illustrates convective activity occurred within all groups; however, much greater activity occurred within groups two and three with the least amount of reflectivity days found in group four (Figure 2; Bentley *et al.*, 2010). The distribution of lightning (i.e. flash density) also corroborates the radar data (Figure 3). Groups two and three appear the most active in terms of both the number of days of composite reflectivity greater than 40 dBZ and also flash density (Figures 2 and 3). Both radar and lightning distributions also show clustering of activity in and around the Atlanta CBD with several nodes or ‘hotspots’ evident in the radar and lightning distributions of groups two and

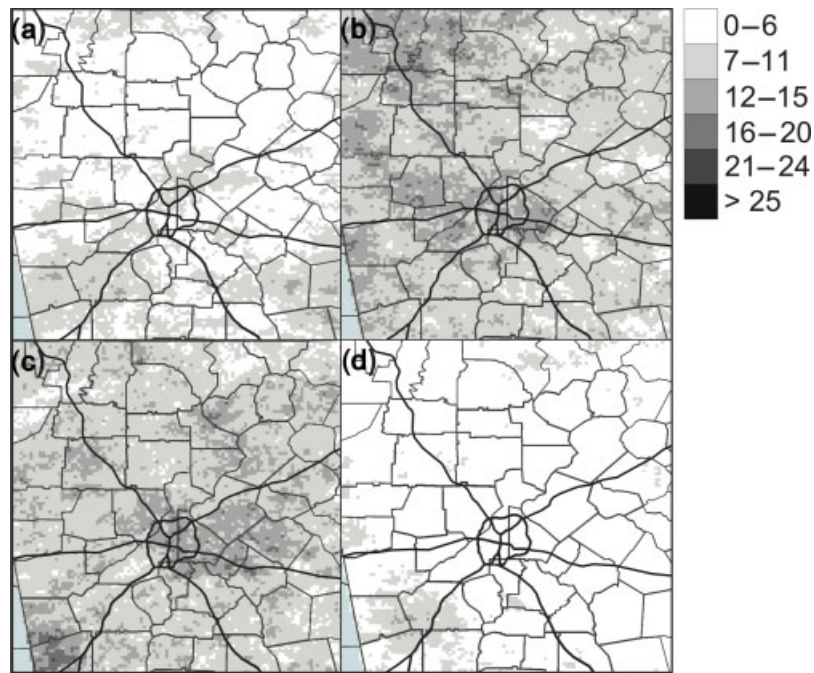


Figure 2. a) The frequency of composite reflectivity (>40 dBZ) days for each 2 km grid cell for group 1 events. b), same as a) except for group 2 events. c), same as a) except for group 3 events. d), same as a) except for group 4 events. This figure is available in colour online at [wileyonlinelibrary.com/journal/joc](http://wileyonlinelibrary.com/journal/joc)

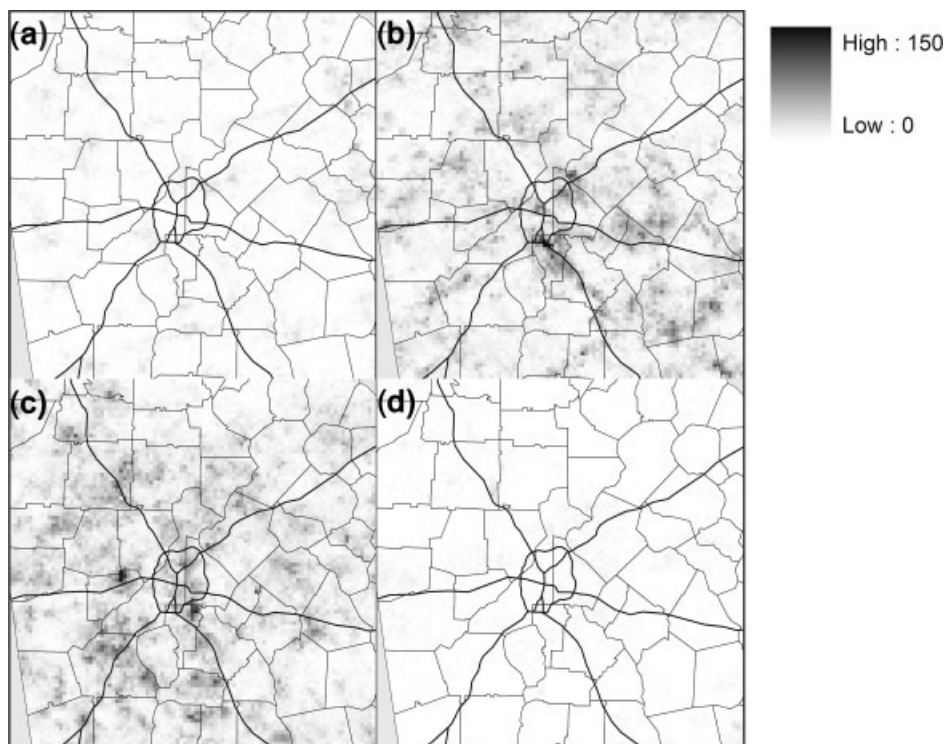


Figure 3. a) Daily gridded flash density ( $2 \times 2$  km) for group 1 events. b), same as a), except for group 2 events. c), same as a), except for group 3 events. d), same as a), except for group 4 events.

three. Curiously, the least active days for radar and lightning occur in groups one and four, when the convective instability is the highest and lowest of the four environments, respectively (Figures 2 and 3). Groups two and three contain over 8000 flashes per day, while group four registers only 132 (Table I).

The thermodynamic environment supports the radar climatology given the stability shown during group four days (Table I). Although group three contains the most number of days with convective activity (41), the average CAPE and lifted index are marginally indicative of strong thunderstorm potential. The spatial distribution of

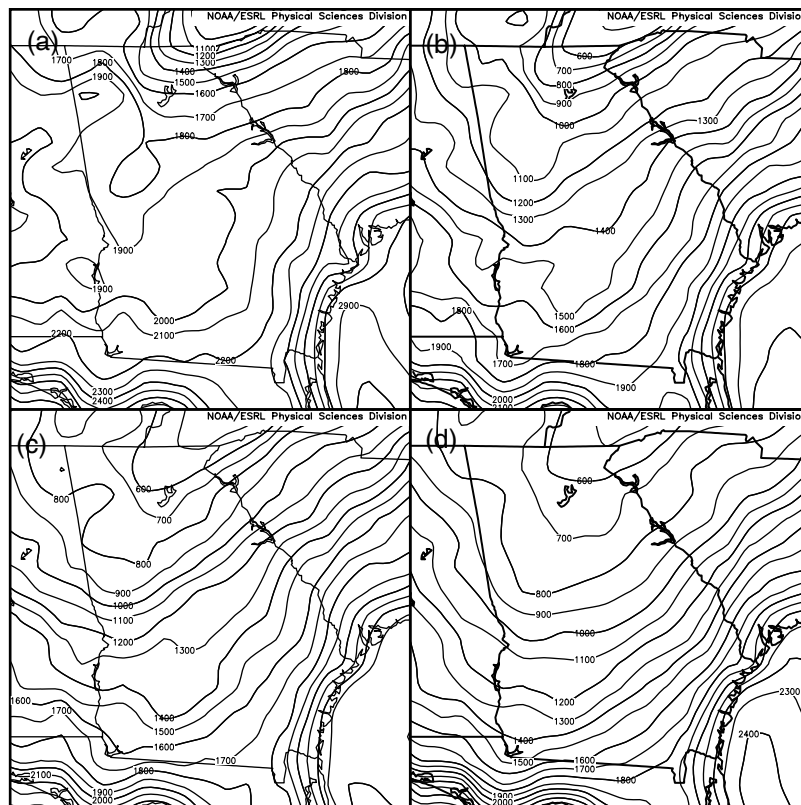


Figure 4. a) Surface-based CAPE ( $\text{J kg}^{-1}$ ) for group 1 events. b), same as a) except for group 2 events. c), same as a) except for group 3 events. d), same as a) except for group 4 events.

CAPE for each group illustrates a general north-south axis through east-central Georgia of increasing values toward the Atlantic coast (Figure 4). Lower values of CAPE are found in the higher terrain of the Appalachians to the northeast of Atlanta. This axis of lower CAPE is oriented northeast to southwest through west-central Georgia in varying degrees depending on the group (Figure 4). Although large differences in CAPE exist between groups, the overall spatial distribution is similar across Georgia.

During periods of thunderstorm activity in proximity to Atlanta, 850 hPa is characterized by light westerly to southwesterly flow found on the north side of an area of high pressure anchored over the deep south (Figure 5). Wind speeds range from 3 to 4  $\text{m s}^{-1}$  over northern Georgia while the 850 hPa temperature ranges from 17 to 18°C and specific humidities from 10.8 to 11.5  $\text{g kg}^{-1}$ . Winds veer to more west-northwesterly at 700 hPa, but remain light, varying between 4.5 and 5.5  $\text{m s}^{-1}$ . The 700 hPa temperatures range from 7.8°C for group 4 to 8.5°C for group one events. The temperature at 500 hPa for group one and two events is, on average, 1 to 2°C colder than groups three and four (Figure 6). This small, but meaningful difference in 500 hPa temperatures is marginally increasing the lapse rates for groups one and two thereby promoting greater instabilities as seen in the thermodynamic indices (Table I). Georgia appears to be under a moderate to strong high-pressure ridge during all groups that

are characterized by light west-northwest 500 hPa winds (5–6  $\text{m s}^{-1}$ ).

## 5. Conclusions

Modelling studies have shown that periods during the warm season and weak synoptic forcing allow the UHI to intensify and therefore augment convective activity close to the urban core (Theilen *et al.*, 2000).

The UHI, building height, and surface roughness likely combine to produce urban core thunderstorms while the UHI-induced circulations on the fringes of the urban land cover lead to increases in suburban storms and bifurcation of some events (Niyogi *et al.*, 2006). When examining the spectrum of synoptic and thermodynamic environments associated with days when thunderstorms developed in proximity to Atlanta, it appears urban convection tends to favour periods of moderate thermodynamic instability. The ‘tails’ of our distribution, made up of groups one and four both contain fewer flashes per day and number of events identified using composite reflectivity (Table I). Curiously, groups one and four are of disparate thermodynamic environments with group one exhibiting strong instability while the small number of group four events occurred in a relatively stable environment. The greatest thunderstorm activity in proximity to Atlanta occurred in groups two and three which are characterized by moderate thermodynamic instability.

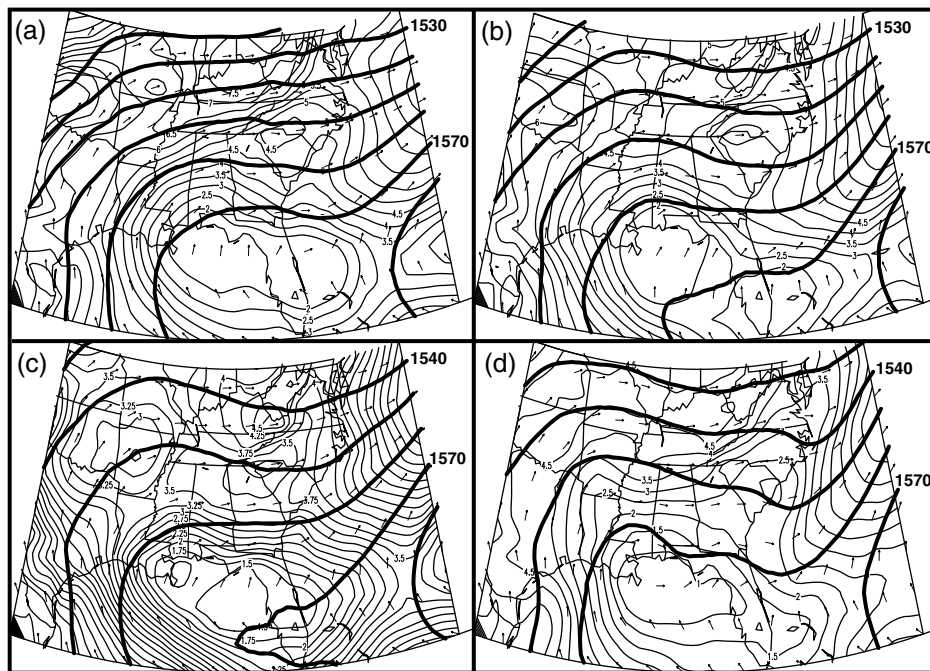


Figure 5. a) 850 hPa geopotential heights (gpm; thick isolines) and winds ( $\text{m s}^{-1}$ ; vectors and isotachs) for group 1 events. b), same as a) except for group 2 events. c), same as a) except for group 3 events. d), same as a) except for group 4 events.

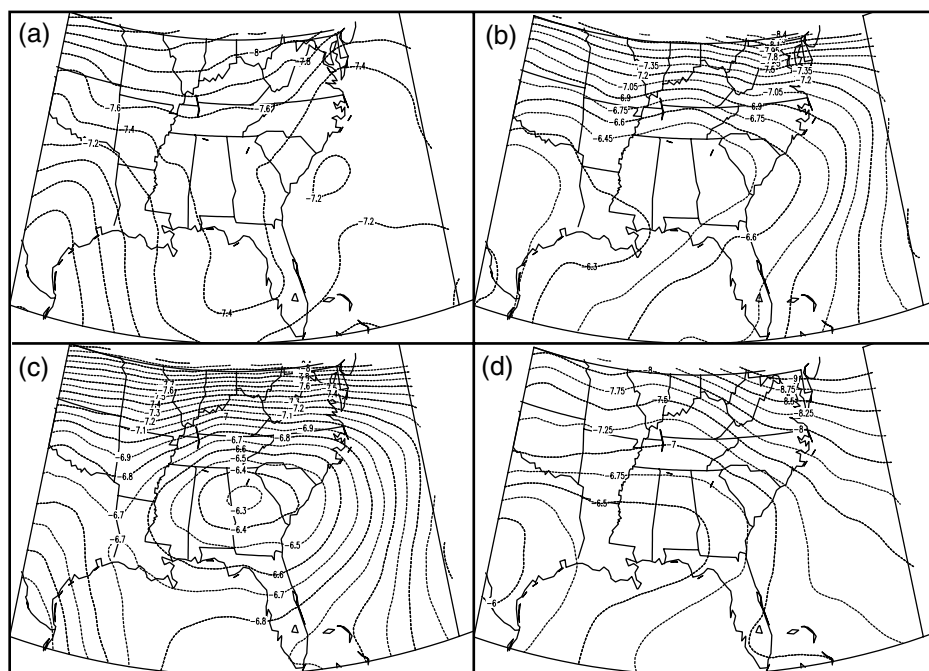


Figure 6. a) 500 hPa isotherms ( $^{\circ}\text{C}$ ) for group 1 events. b), same as a), except for group 2 events. c), same as a) except for group 3 events. d), same as a) except for group 4 events.

The synoptic environments were very similar for all groups with moderate to strong high pressure in place from the surface through 250 hPa. Winds were light and west-northwesterly at all levels for all groups with only subtle differences in moisture and temperature. The greatest differences in temperature were noted at 500 hPa with groups three and four, having slightly warmer environments than groups one and two. This likely increased the lapse rates for group one and

two events increasing the amount of thermodynamic instability present.

Given the relative similarities in the synoptic environments amongst the groups and the propensity for thunderstorm development to occur during moderate thermodynamic instability, evidence suggests that multiple mechanisms are likely influencing the warm-season thunderstorm environment surrounding Atlanta (Shepherd *et al.*, 2010). These factors likely include aerosol size and

concentration, as they can exert a strong influence on the strength and timing of updrafts, downdrafts and thunderstorm development in urban areas (van den Heever and Cotton, 2007; Jin and Shepherd, 2008; Rosenfeld *et al.*, 2008). Studies have shown that aerosols are more numerous on high CAPE days (Lacke *et al.*, 2009). As aerosols increase in concentration, radiatively forced cooling of the surface can act as a negative feedback on the microphysical enhancement of convection (Koren *et al.*, 2008; Altaratz *et al.*, 2010). In addition, cumulus developing in a polluted air mass contain more droplets and tend to live longer, leading to even greater shadowing/cooling of the low-levels (Stevens and Feingold, 2009). A combination of these effects would act to minimize thunderstorm intensity and lightning density during periods of higher instability and aerosol concentration. In this initial investigation of the environments surrounding warm season, synoptically benign thunderstorms occurring in proximity to Atlanta, evidence suggests that there may exist a balance between the magnitude of thermodynamic instability and unaccounted factors such as aerosol size and concentration. The mix of urban and rural aerosols, in combination with ambient moisture in the PBL, control the propagation and longevity of urban thunderstorms (Smith, 1988; van den Heever and Cotton, 2007). In addition, periods of high instability and elevated aerosol concentrations may actually lead to cooling of the PBL and limit the development and intensity of thunderstorm activity in and around Atlanta.

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### References

- Ahijevych DA, Carbone RE, Davis CA. 2003. Regional-scale aspects of the diurnal precipitation cycle. Preprints, *31st International Conference on Radar Meteorology*, Seattle, WA, American Meteorological Society, CD-ROM, 5B.3.
- Altaratz O, Koren I, Yair Y, Price C. 2010. Lightning response to smoke from Amazonian fires. *Geophysical Research Letters* **37**: L07801, p. 6.
- Balling R, Brazel S. 1987. Recent changes in Phoenix summertime diurnal precipitation patterns. *Theoretical and Applied Climatology* **38**: 50–54.
- Bentley ML, Ashley WS, Stallins JA. 2010. Climatological radar delineation of urban convection for Atlanta, Georgia. *International Journal of Climatology* **30**(11): 1589–1594.
- Bentley ML, Stallins JA. 2005. Climatology of cloud-to-ground lightning in Georgia, USA, 1992–2003. *International Journal of Climatology* **25**: 1979–1996.
- Bornstein R, LeRoy M. 1990. Urban barrier effects on convective and frontal thunderstorms. Preprints, *Conf. on Mesoscale Processes*, Boulder, CO, American Meteorological Society, 25–29.
- Dixon PG, Mote TL. 2005. Patterns and causes of Atlanta's urban heat island-initiated precipitation. *Journal of Applied Meteorology* **42**: 1273–1284.
- Elvidge CD, Milesi C, Dietz JB, Tuttle BT, Sutton PC, Nemani R, Vogelmann JE. 2004. U.S. constructed area approaches the size of Ohio. *EOS Transactions AGU*, 85, 233.
- Falconer PD. 1984. A radar-based climatology of thunderstorm days across New York state. *Journal of Climate and Applied Meteorology* **23**: 1115–1120.
- Jin M, Shepherd JM. 2008. Aerosol relationships to warm season clouds and rainfall at monthly scales over east China: Urban land versus ocean. *Journal of Geophysical Research* **113**: D24S90, p. 12.
- Koren I, Martins JV, Remer LA, Afargan H. 2008. Smoke Invigoration Versus Inhibition of Clouds over the Amazon. *Science* **321**(5891): 946–949.
- Lacke MC, Mote TL, Shepherd JM. 2009. Aerosols and associated precipitation patterns in Atlanta. *Atmospheric Environment* **43**: 4359–4373.
- Lance GN, Williams WT. 1966. Computer programs for hierarchical polythetic classification (Similarity analyses). *Computer Journal* **9**: 60–64.
- Mesinger F, DiMego G, Kalnay E, Mitchell K, Shafran PC, Ebisuzaki W, Jovic D, Woollen J, Rogers E, Berbery EH. 2006. North American regional reanalysis. *Bulletin of the American Meteorological Society* **87**: 343–360.
- Moncrieff MW, Miller MJ. 1976. The dynamics and simulation of tropical cumulonimbus and squall lines. *Quarterly Journal of the Royal Meteorological Society* **102**: 373–394.
- Mote TL, Lacke MC, Shepherd JM. 2007. Radar signatures of the urban effect on precipitation distribution: a case study for Atlanta, Georgia. *Geophysical Research Letters* **34**: L20710.
- Niyogi D, Pielke Sr RA, Adegoke J, Chang HI, Chase T, Douglas E, Gupta M, Marshall C, Matsui T, Pyle PC, Shepherd M. 2006. Considering the Role of Aerosols and Land-Atmosphere Interactions Related to Agriculture and Urbanization in Climate Studies. *American Association of Geographers Annual Meeting*, Chicago, March 2006.
- Ntelekos AA, Smith JA, Krajewski WF. 2007. Climatological analyses of thunderstorms and flash floods in the Baltimore metropolitan region. *Journal of Hydrometeorology* **8**: 88–101.
- Orville RE, Huffines G, Nielsen-Gammon J, Zhang RY, Ely B, Steiger S, Phillips S, Allen S, Read W. 2001. Enhancement of cloud-to-ground lightning over Houston, Texas. *Geophysical Research Letters* **28**: 2597–2600.
- Parker MD, Kniviel JC. 2005. Do meteorologists suppress thunderstorms? Radar-derived statistics and the behavior of moist convection. *Bulletin of the American Meteorological Society* **86**: 341–358.
- Peppler RA. 1988. A review of static stability indices and related thermodynamic parameters. *Illinois State Water Survey Misc. Publ. 104*, p. 87. [Available from Illinois State Water Survey, Champaign, IL 61820].
- Rickenbach TM, Rutledge SA. 1998. Convection in TOGA COARE: Horizontal scale, morphology, and rainfall production. *Journal of Atmospheric Science* **55**: 2715–2729.
- Roberts RD, Wilson JW. 1989. A proposed microburst nowcasting procedure using single-Doppler radar. *Journal of Applied Meteorology* **28**: 285–303.
- Rosenfeld D, Lohmann U, Raga GB, O'Dowd CD, Kulmala M, Fuzzi S, Reissell A, Andreae MO. 2008. Flood or drought: How do aerosols affect precipitation? *Science* **321**(5894): 1309–1313.
- Selover N. 1997. Precipitation patterns around an urban desert environment topographic or urban influences? *Proceedings of the Association of American Geographers Conference*, Fort Worth, TX, Association of American Geographers.
- Shem W, Shepherd JM. 2009. On the impact of urbanization on summertime thunderstorms in Atlanta: Two numerical model case studies. *Atmospheric Environment* **43**(28): 4359–4373.
- Shepherd JM. 2005. A review of current investigations of urban-induced rainfall and recommendations for the future. *Earth Interactions* **9**: 1–27.
- Shepherd JM, Burian SJ. 2003. Detection of urban-induced rainfall anomalies in a major coastal city. *Earth Interactions* **7**: 1–17.
- Shepherd JM, Stallins JA, Jin M, Mote TL. 2010. Urbanization: Impacts on clouds, precipitation, and lightning. *Monograph on Urban Ecological Ecosystems* Jacqueline Peterson, Astrid Volder (eds). American Society of Agronomy-Crop Science Society of America-Soil Science Society of America: p. 354.
- Sheridan SC. 2002. Redevelopment of a weather-type classification scheme for North America. *International Journal of Climatology* **22**: 51–68.
- Smith MH. 1988. Air parcel thermodynamic properties and aerosol particle concentrations in the maritime atmospheric boundary layer. *Quarterly Journal of the Royal Meteorological Society* **114**: 771–780.

- Stallins JA, Bentley ML. 2006. Urban lightning climatology and GIS: an analytical framework from the case study of Atlanta, Georgia. *Applied Geography* **26**: 242–259.
- Stallins JA, Rose S. 2008. Urban Lightning: Current Research, Methods, and the Geographical Perspective. *Geography Compass*, DOI:10.1111/j.1749–8198.2008.00110.x.
- Stevens B, Feingold G. 2009. Untangling aerosol effects on clouds and precipitation in a buffered system. *Nature* **461**: 607–613.
- Thielen J, Wobrock W, Gadian A, Mestayer PG, Creutin JD. 2000. The possible influence of urban surfaces on rainfall development: A sensitivity study in 2D in the mesogamma scale. *Atmospheric Research* **54**: 15–39.
- Van Den Heever SC, Cotton WR. 2007. Urban aerosol impacts on downwind convective storms. *Journal of Applied Meteorology and Climatology* **46**: 828–850.