Patterns and Causes of Atlanta’s Urban Heat Island–Initiated Precipitation  

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ABSTRACT  
Because of rapid growth and urbanization of Atlanta, Georgia, over the past few decades, the city has developed a pronounced urban heat island (UHI) that has been shown to enhance and possibly to initiate thunderstorms. This study attempts to find patterns and causes of Atlanta’s induced precipitation that might not have been initiated otherwise. Land use maps, radar reflectivity, surface meteorological data, upper-air soundings, and airmass classification (spatial synoptic classification) types are all used to determine when, where, and why precipitation is initiated by Atlanta. Findings illustrate significant spatial and temporal patterns based on a 5-yr climatological description of events. July had the most events, with a diurnal peak just after local midnight. Low-level moisture, rather than UHI intensity, appears to be the most important factor for UHI-induced precipitation. However, UHI intensity also plays an important role. Events tended to occur under atmospheric conditions that were more unstable than those on rain-free days but not unstable enough to produce widespread convection.

1. Introduction  
In the past 30 years, Atlanta, Georgia, has rapidly become the leader among southeastern U.S. centers for commerce, industry, and transportation. The population of the 20-county area (Fig. 1), defined by the U.S. Census Bureau as the Atlanta metropolitan statistical area, has increased by 38.9% since 1990, by more than 130% since 1970, and by 313% since 1950 to make it the most populated urban area in the southeastern United States. According to Yang and Lo (2002), forested area in Atlanta decreased by more than 20% from 1973 to 1997. During that time, commercial development and low-density residential areas (suburbs) both doubled. In 1998, the Sierra Club ranked Atlanta as the “most sprawl-threatened city” in the country (Sierra Club 1998). Further, during the 1970s and 1980s, Atlanta had been losing green space to development at a rate faster than any other metropolitan area in world history (Hartshorn and Ihlafeldt 1993).

As more land becomes urbanized, an urban heat island (UHI) may develop, causing the city to remain consistently warmer than its surroundings. This phenomenon is created by changes in the natural environment caused by urban development and deforestation. Several studies have shown significant UHIs in major cities across the globe (e.g., Bornstein 1968; Oke 1973; Draxler 1986; Balling and Cerveny 1987; Lo et al. 1997; Bornstein and Lin 2000; Morris et al. 2001). In addition, much research has been done to determine how UHIs affect urban precipitation (Changnon et al. 1976; Huff and Changnon 1972, 1973; Huff and Vogel 1978; Bornstein and Lin 2000; Shepherd et al. 2002). In particular, Huff and Changnon (1973) studied nine U.S. cities (St. Louis, Missouri; Chicago, Illinois; Indianapolis, Indiana; Cleveland, Ohio; Washington, D.C.; Baltimore, Maryland; Houston, Texas; New Orleans, Louisiana; and Tulsa, Oklahoma) and observed urban-induced increases in precipitation for all of the cities except Indianapolis and Tulsa. The areas of increased precipitation ranged from directly over the urban center to 80 km downwind of the urban center. In more recent work, Bornstein and Lin (2000) reported three events of UHI-initiated precipitation in Atlanta during a 9-day period in July and August of 1996. The events listed by Bornstein and Lin (2000) were all slightly downwind of the urban area, and they were shown to have initiated during strong UHI conditions and relatively weak, converging surface winds (<4 m s⁻¹), likely created along UHI-induced surface temperature gradients. Since that time, Atlanta has been widely publicized as “creating its own weather” (Mullen 1999; Chang 2000; Daly 2000).

It has already been shown (Bornstein and Lin 2000) that the UHI of Atlanta may be able to initiate thunderstorms. This study attempted to determine whether Atlanta’s UHI initiates anomalous precipitation regularly, whether temporal and spatial patterns are exhibited by the UHI-initiated precipitation, and whether any sug-
gestions can be made as to why the events in question occur when and where they do. The results presented here should lead to a better understanding of the local hydroclimate of Atlanta stemming from its UHI and support further investigation into the subject of UHI-induced precipitation. Further, conclusions from this project may also allow forecasters to predict more of these anomalous precipitation events.
2. Background

Anthropogenic alteration of the urban climate has been documented for nearly two centuries (Howard 1833). A UHI occurs when the urbanized area of a city exhibits higher temperatures than the surrounding rural areas. Oke (1987) states that the most notable feature of an urban heat island is the reduced cooling during late afternoon and evening hours under relatively constant weather conditions. The reason given for this moderated cooling is the reduced sky-view factor of urban buildings. When compared with open, horizontal surfaces (such as most rural areas), urban buildings have much less of their surface area exposed to open air and have more area facing other warm building surfaces. Therefore, radiative loss of heat is reduced, and this reduction results in higher nocturnal minimum temperatures when compared with rural areas. The urban area is also slower to warm up after sunrise because of many building-shaded parts of the city. Therefore, urban–rural temperature differences grow quickly just after sunset and tend to be most pronounced a few hours (3–5 h) after sunset (Oke 1987). On an annual basis, Gallo and Owen (1999) found the greatest urban–rural temperature difference (with regard to monthly maximum, minimum, and average temperatures) to occur during the summer months of July and August, based on a study of 28 U.S. cities.

Wind speed plays a vital role in the development of the UHI. Many studies have shown wind speed, along with cloud cover, to be the most important meteorological parameters that affect the development and intensity of the UHI (Ackerman 1985; Moreno-Garcia 1994; Kidder and Essenwanger 1995; Figuerola and Mazzeo 1998). On calm nights, UHI intensity should be inversely related to cloud cover because increased cloudiness may act to minimize radiational cooling in rural areas. Further, wind speeds within the urban canopy may be stronger than in rural areas on relatively calm nights because of the horizontal surface temperature (and, therefore, pressure) gradients between the urban and rural areas. Much like a sea breeze, the anomalously warm urban center creates relatively low air pressure that causes cooler, rural air to converge on the urban center (Oke 1987). Findlay and Hirt (1969) showed that UHI-induced low pressure (due to anomalous heat) within urban areas resulted in light flow of air from the rural areas toward the urban center during weak synoptic flow. The caveat, during weak synoptic flow, proves to be very important. As surface winds encounter the increased roughness of urban areas, horizontal speeds tend to notably decrease (Landsberg 1981; Oke 1987). Therefore, it becomes clear that urban areas should cause surface winds to decrease under significant synoptic flow and increase under weak synoptic flow.

a. Urban impacts on precipitation

The first documented case of urban-induced changes in precipitation was by Landsberg (1956) in Tulsa, Oklahoma. He found indications that the city was causing increased precipitation. Urban-induced changes in rainfall tend to be subtle and less detectable than changes in visibility, winds, and temperature. However, Huff and Changnon (1973) found measurable precipitation enhancements in six of the eight cities studied. The results of their study show that even though all intensities of daily rainfall appeared to be increased by the effects of urban areas, the most pronounced modifications tended to be on days with moderate to heavy natural rainfall. Therefore, one could conclude that the UHI acts primarily to enhance rainfall rather than initiate it. Likewise, results from the Metropolitan Meteorological Experiment (METROMEX) project indicate that the urban area of St. Louis, Missouri did not necessarily increase the number of precipitation events, but, instead, stimulated events that were already occurring. Possible causes of the increased precipitation were suggested as increased condensation nuclei over the city, increased roughness causing surface convergence, and instability from urban heating (Changnon 1981).

Bornstein and LeRoy (1990) found the urban heat island of New York City (NYC), New York, affected both formation and movement of summer daytime thunderstorms. Under calm regional winds, the NYC UHI initiated convective cloud formation and produced a radar echo maximum directly over the urban area. However, the Bornstein and LeRoy (1990) study also showed that preexisting thunderstorms moving toward the city tended to bifurcate and move around the urban area, which they attributed to a building-induced divergence effect. This pattern resulted in radar echo maximums along the edges and downwind of the city, with a minimum directly over the urban area (Bornstein and LeRoy 1990). Shepherd et al. (2002) found that Atlanta produced a 19.5% increase in precipitation downwind of the metropolitan area when compared with an upwind control area during the warm seasons of 1998–2000. However, Shepherd et al. (2002) analyzed monthly averages using the Tropical Rainfall Measuring Mission satellite’s precipitation radar and did not distinguish among urban-initiated precipitation, preexisting precipitation, and specific forcing mechanisms.

The UHI may also affect precipitation patterns because of increased condensation nuclei and surface convergence associated with increased roughness. It was previously thought that increased condensation nuclei would lead to increased condensation and, therefore, increased precipitation downwind of the urban area (Landsberg 1956; Changnon 1981; Mather 1991). However, more recent studies (Reuter and Guan 1995; Reisin et al. 1996) show little to no increase in precipitation caused by increased condensation nuclei. Rosenfeld (2000) states that increased condensation nuclei, from pollution, create a greater number of small droplets but much less coalescence and drop formation. Therefore, condensation nuclei created by urban pollution may create droplets that do not become large enough to fall as
precipitation and may, ultimately, create regions of suppressed precipitation downwind of the source.

b. Project ATLANTA

The Atlanta Land Use Analysis: Temperature and Air Quality project (project ATLANTA) was a study funded by the National Aeronautics and Space Administration Earth Observing System that began in 1996. The purpose was to determine Atlanta’s effects on local climate and air quality. The project incorporated assessment of land cover/land use change, as determined from remote sensing data with temporal numerical model simulations, to understand better the effects of Atlanta’s growth on local and regional climate and air quality (Quattrochi and Luvall 1997).

Based on data collected during project ATLANTA, the Atlanta UHI produces temperatures up to 5°C greater than the surrounding areas (Bruce 1999). In addition to remotely sensed data, Bornstein and Lin (2000) used weather stations set up by the National Weather Service (NWS) and the Georgia Automated Environmental Monitoring Network (GAEMN; Hoogenboom 1996). According to Bornstein and Lin (2000), under nearly calm regional flow, a relative low pressure may be created over the city by the anomalous high temperatures of the UHI, and cooler air rushes into the urban area, which causes warm air to rise. This vertical motion can create convective thunderstorms that produce precipitation maximums over the city, and it is most pronounced at night when the UHI is strongest (Bornstein and Lin 2000). In converse, when regional flow is significant, winds tend to diverge around the city because of increased surface roughness. This phenomenon creates precipitation maximums on the lateral and downwind edges of the city, with a minimum located directly over the urban area.

Determining how a UHI increases urban precipitation has yielded mixed results that have suggested increased condensation nuclei from urban pollutants (Landsberg 1956; Changnon 1981; Mather 1991), surface convergence caused by increased surface roughness (Changnon 1981), and instability caused by urban heating (Changnon 1981; Bornstein and LeRoy 1990; Bornstein and Lin 2000). Nevertheless, it is likely that most of these causes are valid, but some apply more to certain cities because they vary in their building shapes, sizes, locations, geometries, and so on. Further, the amount of green space, and subsequent moisture, in a city should significantly alter the effects of the UHI and associated precipitation.

3. Method

The purpose of this study was to identify UHI-initiated precipitation events and then to use observational data from the events to determine possible reasons for their existence. National radar mosaics based on Weather Surveillance Radar-1988 Doppler (WSR-88D) data were analyzed to identify possible UHI-initiated precipitation over the Atlanta area during periods of weak synoptic flow. Radar reflectivity was used because it is able to display data from the entire study area at 15-min intervals. Hourly data from surface weather stations in the Atlanta area, surface meteorological maps, and upper-level meteorological charts were used to help to determine periods of weak flow. The surface station data were also used to understand the surface environment in which these events occurred. Radiosonde observations from the NWS Forecast Office in Peachtree City, Georgia (KFFC), were used to determine upper-level wind speeds and a vertical temperature profile to illustrate the stability and moisture content of the lower atmosphere during these events. Data from an airmass classification technique based on typical characteristics of each air mass were used to determine what types of air masses are associated with initiation of convective precipitation resulting from Atlanta’s UHI.

a. Radar reflectivity

The 2-km 15-min radar mosaics for this project were provided by the Global Hydrology Resource Center (GHRC) at the Global Hydrology and Climate Center, Huntsville, Alabama. The GHRC generates composite products in hierarchical data format for the continental United States based upon composites of radar reflectivity data received from Weather Services International Corporation every 15 min. The 2-km pixels within the mosaics are assigned 1 of 16 categories based on the original reflectivity value. The data files were viewed using software written in Research Systems, Inc., Interactive Data Language, version 5.5. This software was used to zoom in on the state of Georgia and its county borders rather than looking at the entire national mosaic.

b. Surface station and upper-air data

This research makes use of 10 surface meteorological stations in and around Atlanta that report data at least once every hour. Five of these stations are part of the Automated Surface Observing System sponsored by the Federal Aviation Administration, NWS, and Department of Defense. Data from these stations were obtained from the National Climatic Data Center in Asheville, North Carolina, and the Southeast Regional Climate Center in Columbia, South Carolina. The remaining surface station data used in this project were obtained from the GAEMN at the University of Georgia campus in Griffin. GAEMN data are available in 15-min intervals.

Surface meteorological charts (0000 and 1200 UTC) that correspond to each UHI precipitation event were used to help to determine the existence and location of any surface fronts, boundaries, or other forcing mechanisms. These charts were accessed from the Unisys,
Inc., weather image and map archive (obtained online at http://weather.unisys.com/archive).

Upper-air observations for the Atlanta area were based on radiosonde data taken at KFCC, approximately 40 km south-southwest of downtown Atlanta (Fig. 1). This project makes use of KFCC radiosonde data (usually recorded at 0000 and 1200 UTC) for each event day to identify atmospheric environments conducive to UHI-initiated precipitation. Upper-air data for this study were provided jointly by the Forecast Systems Laboratory in Boulder, Colorado, and the National Climatic Data Center.

c. Synoptic classification data

To determine the type of air masses that were most commonly associated with UHI-induced precipitation, air mass types were identified for each event. The spatial synoptic classification (SSC) method was employed to distinguish air mass types (Sheridan 2002). SSC requires initial identification of the distinctions among the major air masses that traverse the region as well as their typical meteorological characteristics. Source region delineation is less important for this method because air masses tend to be modified as they traverse from their source region, although SSC categories are relatively synonymous with traditional air mass classification categories [e.g., dry polar (DP) is synonymous with continental polar (cP)].

SSC categorizes days into one of the following six air mass types: DP, dry temperate (DM), dry tropical (DT), moist polar (MP), moist temperate (MM), and moist tropical (MT). Dry polar is the coldest, and often the driest, air mass in a region. Dry temperate air is typically associated with mild, dry conditions, DT is very hot and dry air, and MP is cooler, more humid, and cloudy. Moist temperate is similar to MP, but with much higher temperatures and dewpoints. Moist tropical represents warm, humid conditions similar to the traditional maritime tropical (mT) air mass type. Atmospheric instability and convective activity are common within the MT air mass (Kalkstein et al. 1996). A seventh category, transitional (TR), is applied to days during a period of transition between two air masses.

d. Land use/land cover data

This study utilizes land use imagery from 1997 (Yang and Lo 2002) to understand better where UHI-initiated precipitation events begin in relation to the urban areas of Atlanta. The 1997 land use image is based on Landsat thematic mapper imagery from 29 July 1997. However, because of clouds in the initial image, another image taken on 2 January 1998 was used to supplement the 1997 image (Yang and Lo 2002). Nine land use categories (high-density urban, low-density urban, cultivated–exposed land, cropland–grassland, golf courses, evergreen forest, mixed forest, deciduous forest, and open water) were used by Yang and Lo (2002), but this study simplifies the categories into high-density urban, low-density urban, nonurban, and open water.

e. Event selection

The number of days included in this study was restricted to the warm-season months of May–September, because the UHI is most pronounced in summer (Huff and Changnon 1972; Gallo and Owen 1999). In addition, it is during the summer months that Georgia is typically under the influence of the Bermuda high, and precipitation is almost always due to convective storms that are not associated with synoptic-scale forcing (Outlaw and Murphy 2000). Days that were not considered to have weak synoptic flow were removed from the analysis to avoid precipitation events that were significantly influenced by features other than the UHI. This study partially adopts the approach of Brown and Arnold (1998) to determine weak synoptic flow. In their study of nonclassical mesoscale circulations and convection initiated by land cover boundaries, weak synoptic flow was defined as: 1) no synoptic surface forcing mechanism identifiable within 500 km; 2) 500-hPa wind speeds within the region of <7.72 m s$^{-1}$ (<15 kt); and 3) surface wind speeds of <5.14 m s$^{-1}$ (<10 kt). However, Vukovich (1975) points out that, although UHI intensity decreases with increased vertical wind shear, clear nocturnal skies during synoptic high pressure should allow the differential heating processes of a typical UHI to prevail. Therefore, this study does not remove days with stronger upper-level winds, because the UHI, although perhaps weakened, should remain the dominant factor under synoptic high pressure (Vukovich 1975). Further, past studies of UHI-altered precipitation (Changnon 1981; Bornstein and LeRoy 1990; Bornstein and Lin 2000) did not remove days from analysis based on upper-level flow.

Radar reflectivity data from summer days with weak synoptic flow were analyzed to find precipitation cells that were initiated within the 20-county area of metropolitan Atlanta. Atlanta is a sprawling urban area, but there are many parts of the 20-county area that are not urban (Fig. 1), and so the selection of events did not require that they exist over an urban area. Events were sought based primarily on their reflectivity appearance (size and shape) and location (within Atlanta and isolated from other cells) at initiation in order to identify precipitation events that were likely induced—not simply enhanced—by the urban area. Moreover, events were selected so that it could not be argued that they were initiated by any means other than the UHI. For example, even if a cell was initiated directly over downtown Atlanta, it was not included in the study if it occurred at 1600 eastern standard time (EST) and there were other cells across the region. It would be reasonable to assume that such a storm is likely due to general daytime heating and instability and is not limited to
urban areas. Further, even if a study day had no major surface forcing mechanisms identified on the synoptic chart but there was some apparent influence of an atmospheric boundary (e.g., boundaries identified on radar), that event was not included. This study contains only precipitation events that were relatively isolated and were clearly located over the Atlanta area. Large (i.e., supercells), multicell, and stratiform precipitation events were not included in the study.

f. Spatial analysis

Once UHI-initiated storms were identified, each cell was recorded based on its initiation time, termination time, initiation latitude, initiation longitude, and initiation county or counties. Termination location is of little relevance to this study because the primary objective is to seek whether, when, and where precipitation cells are initiated by UHI. This study focuses on the initiation points of convective precipitation rather than on the entire storm tracks.

Each event was plotted according to its initiation location in ESRI Company ArcView GIS, version 3.2, proprietary software to illustrate the spatial distribution of these events. The events were also overlaid on the 1997 Landsat image of Atlanta as were county boundaries and interstate highways. ArcView was then used to illustrate the location of UHI-initiated precipitation events relative to urban areas.

Two stations were chosen to represent the urban and rural environments. Based primarily on the 1997–98 land use image, the Clark Atlanta University station is in a high-density urban location and the Hal B. Wansley Power Plant in Roopville, Georgia, is in a representatively rural location. Both stations are part of the GAEMN network, and so their instrumentation is identical. Data from the two stations were compared to determine whether the urban site consistently experienced conditions that are significantly different from those of the rural site.

g. Atmospheric environment

Because sounding data are usually available for 0000 and 1200 UTC only, skew $T$–log$p$ diagrams were created for the observation times immediately before and after each UHI precipitation event. Nine stability indices were calculated for each sounding to determine whether convective precipitation was expected for each event day and whether any of the indices is able consistently to predict UHI-initiated precipitation. The stability indices used in this study are the Showalter index, lifted index, severe-weather threat index, $K$ index, cross totals, vertical totals, total totals, convective available potential energy, and convective inhibition. In addition, average soundings were calculated based on all UHI-induced precipitation days and on all days included in the study. Average temperature and dewpoint soundings were calculated for all days. The temperature and dewpoint values were then aggregated into 20-hPa layers, and each pressure level was labeled based on the median pressure within that group. For example, the layer ranging from 100 to 119 hPa was labeled level 110. For the purposes of plotting a skew $T$–log$p$, a mean pressure value was calculated for each group based on the pressure levels included within that group. Each group’s temperature and dewpoint were determined by calculating the mean of all available observations within the 20-hPa range of that group. After the two average soundings were completed, the two files were merged based on like pressure groups. Last, mean group temperature and dewpoint values for the average total period sounding were subtracted from the average UHI sounding to find the temperature and dewpoint differences between the two soundings at each level. The two average soundings were compared to find any atmospheric characteristics that were unique to UHI-induced precipitation days.

Airmass types, according to the SSC, that were present during the day of, and the 2 days prior to, each UHI-initiated precipitation event were analyzed to determine whether these events occurred under warmer, more humid air masses and/or whether the events were preceded by warmer/cooler and moister/drier air.

It was hypothesized that a warm, relatively dry air mass (such as airmass type DT) might create a stronger UHI because of the lower specific heat value of drier air, and that may, in turn, enhance the likelihood of precipitation initiated by the UHI. Therefore, the mean urban–rural temperature difference (or UHI intensity) was calculated for each airmass type based on the 24-h mean temperature differences between the urban and rural locations for every day of the study period.

The mean UHI intensity was also calculated for each airmass type based on the nocturnal (1600–0800 EST) mean temperature difference between the urban and rural locations for every day of the study period. This calculation was done to determine what airmass types were more conducive to stronger UHI intensities because moisture content likely plays a large role in whether urban temperatures can climb much higher than rural temperatures.

The application of this method and use of these data should yield a better understanding of when, where, and why UHI-initiated precipitation occurs in Atlanta. This approach goes beyond previous research because it analyzes each individual event over the course of 5 yr to determine exactly when and where these events occur. In addition, the atmospheric environment associated with each event is compared with other events and with average days.

4. Results

This study included 765 days, but 569 days were deemed to have synoptic flow weak enough to be included in the study based on the proximity of no surface
Fronts, strong boundaries, or tropical systems near the Atlanta area. Based on research by Bornstein and Lin (2000), it was hypothesized that there would likely be many events over the 5-yr period. Although there were not as many events as anticipated, there were some significant patterns in surface and upper-air data associated with these days. Further, these patterns differed from average days throughout the study period.

**a. UHI-initiated precipitation events**

During the warm seasons of 1996–2000, 37 events of UHI-initiated precipitation were identified in the Atlanta area based on radar reflectivity. These events occurred during 20 separate days (3.5% of all study days) in 12 separate counties.

This study found that the greatest urban development followed major transportation routes (Fig. 1). Therefore, to determine each event’s proximity to urban areas, buffers of 5, 10, and 15 km were set up around the major limited-access highways in Atlanta (Fig. 2). Based on this analysis, the majority (56.8%) of events in this project occurred less than 5 km from major urban development and 27% were within 10 km (Table 1). Figure 2 shows the location of each event based on the latitude and longitude of the storm center.
TABLE 1. UHI-induced precipitation events aggregated by distance from major limited-access highways in the metropolitan Atlanta area.

<table>
<thead>
<tr>
<th>Distance (km)</th>
<th>No. of events</th>
</tr>
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<tr>
<td>&lt;5</td>
<td>21</td>
</tr>
<tr>
<td>5 &lt; 10</td>
<td>10</td>
</tr>
<tr>
<td>10 &lt; 15</td>
<td>5</td>
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<tr>
<td>&gt;15</td>
<td>1</td>
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</table>

The UHI-induced precipitation events recorded in this project illustrate expected patterns with respect to occurrence times (Fig. 3). Most of these events occurred during the predawn hours, with only three events evident between the hours of 0900 and 1900 EST. This pattern is directly opposite to that of typical summertime convective precipitation in Georgia according to Outlaw and Murphy (2000), who analyzed 10 yr (1985–94) of July radar data from Athens and Waycross, Georgia. They found that July convective precipitation across northern Georgia most often began around 1100 EST, with only two convective initiations occurring from 2000 to 0200 EST. During their 10-yr study, 84% of convective precipitation events were initiated between 0700 and 1500 EST. The difference between typical Georgia summertime convective precipitation and UHI-induced convective precipitation is consistent with previous research by Bornstein and Lin (2000) that suggested Atlanta’s UHI caused more nocturnal thunderstorms. However, it should be noted that possible events that may have occurred during periods of widespread general convection were left out of the study because of the inability to distinguish between UHI-induced precipitation and general convective precipitation. Therefore, the results of this study may show a larger fraction of nocturnal events.

In addition to illustrating patterns of occurrence during predawn hours, UHI-induced precipitation events documented in this study show a maximum number of events during July (Fig. 4). Every year in the study period experienced events during July. September conversely is the only month included in the study that is without a single documented UHI-initiated precipitation event.

Even though this study covers only 5 yr, there is significant annual variation in the number of UHI-initiated precipitation events (Fig. 5). The most events occurred in 1996 and 1997, and then 1998 saw a sharp drop. The numbers gradually increased each year thereafter. It should also be noted that the last 3 yr of this study each had three or fewer event days. The decreased number of event days after 1997 could be explained by the intense drought that Georgia was experiencing during the 1998–2000 period. According to the Georgia Department of Natural Resources (2001), the worst drought in Georgia’s history began around May of 1998 and continued to worsen through 2000 in which year some locations reported total rainfall deficits near 127 cm (50 in.). Although there certainly may be other causes for the relatively small number of events and event days during the 1998–2000 period, the severe drought seems like a logical explanation. As will be shown later, low-level moisture apparently plays a major role in determining whether Atlanta’s UHI initiated precipitation. A severe drought would significantly lower moisture content near the surface because of decreased evapotranspiration, and so less UHI-induced precipitation was likely because of reduced low-level moisture content created by the widespread drought from 1998 to 2000.

b. Surface analysis

To determine whether UHI-initiated precipitation days experienced greater UHI intensity than did normal warm-season days (Fig. 6), the average urban–rural temperature difference (based on data from the stations at Clark Atlanta University and Wansley Power Plant) for both types of days were graphed and compared by hour. A difference-of-means test was conducted to determine whether there were significant differences (confidence level $\alpha = 0.05$) between the UHI intensity on event days and UHI intensity on an average day. Because both the mean temperature and standard deviation could be calculated for each event, the standard normal distribution ($Z$ score) method was used to compare the UHI intensity for event days and average days. Results show...
that 16 h out of a 24-h day yielded significant differences in UHI intensity between average event days and the average day based on the entire study period. The 8 h that did not yield significant differences were 1900, 2100, 0100, 0200, and 1000–1300 EST. Because one-half of these times (1900, 2100, 0100, and 0200 EST) are during periods with a greater number of events, it seems that UHI-induced precipitation does not necessarily require above-normal UHI intensities. However, it is more likely that UHI intensity is greatest a few hours prior to storm initiation. Therefore, these patterns support the idea that stronger UHI intensities are conducive to UHI-induced precipitation.

Average UHI intensities for each month were also calculated based on all UHI-induced precipitation events and on the total study period. Although July had the weakest UHI intensity based on average UHI-induced precipitation events and on the entire study period, July also had the greatest temperature values for both the urban and rural locations. Therefore, even though the UHI appears to be weaker during July because of smaller urban–rural temperature differences, the urban area was actually warmer during July than any of the other months. However, the rural site was also much warmer during July. Because July experienced more events and event days than any other month, it seems that a greater UHI intensity does not necessarily yield more UHI-initiated precipitation.

c. Upper-air analysis

Upper-air data for this project are based primarily on 0000 and 1200 UTC soundings released from KFFC. It was hypothesized that sounding data would likely illustrate that Atlanta’s UHI initiated precipitation when low-level temperature and moisture values were higher than average. Such a situation would have required an intense UHI and a moist air mass; those types of conditions could be the result of a moist tropical air mass.

To find any differences between the average sounding based on observations immediately before and after each UHI-induced precipitation event and the average sounding based on all available observations during the study period, average temperature and dewpoint values at 45 vertical levels were compared for both soundings. Another standard normal-distribution difference-of-means test showed that the two average soundings were significantly different (α = 0.05) from one another throughout the column of the atmosphere. Also, the differences between the two soundings were plotted to create a third average sounding that illustrates the major distinctions of the UHI-initiated precipitation events (Fig. 7). However, it should be noted that the average soundings created for this study include observations from all times of the day into a single average. Although it is possible that certain morning or evening soundings could strongly influence the average (even though there was an equal number of each), it is not likely the low-level temperature and moisture values changed rapidly before or after each UHI-induced precipitation event because of the weak synoptic flow criteria required to include days in this study. Figure 7 shows that the two average soundings were different from one another throughout most of the atmosphere and that the dewpoint is significantly higher throughout the lower half of the atmosphere for the UHI-initiated precipitation sounding. Whereas the average temperatures were significantly different throughout the atmosphere for UHI-induced precipitation days and average days, dewpoint values in the lower atmosphere (below 550 hPa) showed a much larger difference. This result implies that a stronger UHI may be somewhat conducive to UHI-induced precipitation but that moisture content is probably more important. This would also explain the dramatic decrease in events during drought years. In addition, Fig. 7 shows that event days experienced slightly increased lapse rates (5.54°C km⁻¹ for event days and 5.08°C km⁻¹ for average days) below 600 hPa, on average.

Severe-weather indices, calculated based on KFFC sounding data, suggested little or no chance on thunderstorms based on the interpretations of each index by Sturtevant (1995). Therefore, the lack of any stability indices implying thunderstorms on event days suggests that conditions at the relatively rural location of KFFC...
were not conducive to convective precipitation development. The $K$ index was the most consistent predictor based on this study, because 22 of the 39 observations (56.4%) yielded $K$-index values indicating more than just scattered thunderstorms. However, the $K$ index increases as midlevel moisture (i.e., 700 hPa) increases, and so moist air masses, such as those usually over Atlanta during summer months, usually yield higher $K$-index values whether there are UHI-induced storms or not.

Because average event days had above-normal lapse rates but were not unstable enough for stability indices to imply severe weather, it seems that these storms likely occurred when the atmosphere was marginally unstable. This result suggests that UHI-initiated precipitation occurs when the atmosphere is more unstable than usual but is not unstable enough for widespread convection. It is only then that the effects of the UHI are able to induce convection primarily around the city.

d. Spatial synoptic classification

Because of varying moisture content, cloud cover, wind, and temperature, certain airmass types are likely to be more conducive to intense UHIs and UHI-induced precipitation. In addition, it was hypothesized that UHI-induced precipitation may be more frequent when a warm, dry air mass was followed by a humid air mass because warm, dry air would yield a greater UHI intensity and added moisture would aid precipitation formation. Using the SSC to separate different airmass types, this study compares various characteristics of each type and correlates them with UHI-initiated precipitation events.

Predictably, air masses that were drier and warmer yielded the strongest UHI intensities (Table 2). The DT airmass type showed a mean nocturnal urban–rural temperature difference of 3.84°C. The lowest mean temperature difference was produced by MP air masses because of the lower temperatures and higher moisture content. UHI intensities for each airmass type were calculated during the nocturnal hours (1600–0800 EST) because on dry, hot days, the rural area would often be warmer than the urban area for a few daytime hours. Because of this effect, the DT airmass type yielded a lower mean UHI intensity than the MT air mass during the day, even though the UHI of a DT air mass was the most intense once the sun went down. Further, because Oke (1987) showed that UHI intensity is usually most pronounced a few hours after sunset, the nocturnal UHI should be more representative than the daytime UHI. However, there was not sufficient evidence to support the hypothesis that UHI-induced precipitation was more common when a warm, dry air mass was followed by a humid air mass (Table 3). Instead, only 6 (40.0%) of the 15 event days had a relatively dry air mass followed by a moister air mass. In converse, 5 (33.3%) of the 15 days had a relatively moist air mass followed by a drier air mass. There were also 4 (26.7%) days with no change in airmass type over the 3-day period.

When airmass types of UHI-initiated precipitation days are compared with typical summer days, there are some notable differences (Fig. 8). The percentage of MT days is comparable for UHI-initiated precipitation days (40.0%) and the 1996–99 average (43.6%), but there is a notable difference in the percentage of MM, DT, and DM days. The percentage of MM on UHI-induced precipitation days (33.3%) is roughly double the percentage of MM days during the 1996–99 period (17.2%). Dry tropical days also have a higher percentage of UHI-induced precipitation (13.3%) with more than 4 times the average frequency of DT days during the 1996–99 period (3.3%). However, the frequency of DM days (13.3%) was approximately one-half of the fre-
quency of the 1996–99 period (26.4%) with respect to UHI-initiated precipitation. Once again, these results suggest that moist air masses tend to yield UHI-induced precipitation more frequently than dry air masses do. Although warmer temperatures are more conducive to these events than cooler temperatures are, it is the moist air masses, not those with greater UHI intensities, that produce more UHI-initiated precipitation events.

5. Summary and conclusions

During the 5-yr period of this study, there were 37 events of UHI-initiated precipitation identified in Atlanta, and those 37 events were clustered into only 20 days. Based on past research of Atlanta’s UHI (Bornstein and Lin 2000; Yang and Lo 2002), many more occurrences were initially expected given that Bornstein and Lin (2000) identified three events during a 9-day study and Yang and Lo (2002) so clearly illustrated the extent to which Atlanta has urbanized. The severe drought was at least partially responsible for the lower numbers. Nevertheless, spatial and temporal patterns of UHI-induced precipitation seem to follow hypotheses based on past research. Most events occurred during the night and near high-density urban areas.

These events were initially hypothesized to occur primarily when UHI intensities were greatest. Although most of the events did occur on days when UHI intensities were above average, a more significant factor seems to be low-level moisture content. UHI-induced precipitation soundings showed much higher dewpoints (as much as 5°C) below 550 hPa than average days. Further, airmass analysis shows that these events were more frequent under the most humid air masses rather than the ones with the greatest UHI intensities. However, humid air masses tend to yield lower temperatures and weaker UHIs. Therefore, although UHI intensities were not the greatest on event days, they were likely relatively high for the given humid air masses. Also, it is likely that these UHI-induced precipitation events occurred when the atmosphere was only marginally unstable. If the atmosphere is too stable, no convection occurs. If the atmosphere is very unstable, widespread convection occurs regardless of urban influence. However, under weak synoptic flow, if the atmosphere is slightly unstable (subjectively measured by a weak inversion on the morning sounding, high moisture content, and relatively benign stability indices), the anomalous heat of the UHI may act as a focal point for convective initiation. These findings should aid forecasters and researchers in predicting these isolated storms and in determining new ways to moderate urban effects on the atmosphere.

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