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Urban heat islands and summertime convective thunderstorms in Atlanta: three case studies

Robert Bornstein*, Qinglu Lin

Department of Meteorology, San Jose State University, San Jose, CA 95192, USA

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Abstract

Data from both 27 sites in the Atlanta mesonet surface meteorological network and eight National Weather Service sites were analyzed for the period from 26 July to 3 August 1996. Analysis of the six precipitation events over the city during the period (each on a different day) showed that its urban heat island (UHI) induced a convergence zone that initiated three of the storms at different times of the day, i.e., 0630, 0845, and 1445 EDT. Previous analysis has shown that New York City (NYC) effects summer daytime thunderstorm formation and/or movement. That study found that during nearly calm regional flow conditions, the NYC UHI initiates convective activity. Moving thunderstorms, however, tended to bifurcate and to move around the city, due to its building barrier effect. The current Atlanta results thus agree with the NYC results with respect to thunderstorm initiation. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Urban precipitation; Urban heat islands; Urban convergence zones

1. Introduction

The overall goal of Project ATLANTA (ATlanta Land use Analysis: Temperature and Air quality) is investigation of regional climate and air quality impacts from the past, current, and future urbanization of Atlanta, Georgia (Quattrochi et al., 1998). Coordinated studies at partner research groups involve:

- satellite-derived land-use analyses (20 years of data) to detect changes in urbanization and surface characteristics (e.g., albedo)
- regional urban climate impact detection from urban heat island (UHI), wind, and cloud data
- changes in air pollutant emission patterns
- changes in regional air quality patterns
- mesoscale meteorological modeling of observed and future meteorological patterns
- regional air quality modeling of observed and future air quality patterns.

The sub-study reported in this paper involved the use of meteorological observations taken during the Atlanta Olympics (26 July–3 August 1996) to investigate interactions of the: Atlanta UHI, its induced convergence zone, and convective thunderstorm initiation.

Analysis by Bornstein and LeRoy (1990) has shown that New York City (NYC) effects both summer daytime thunderstorm formation and movement. During conditions with nearly calm regional flows, the NYC UHI initiated convective activity, thus producing a radar echo frequency maximum over the City. Moving thunderstorms, however, bifurcated and moved around the city due to a building-barrier-induced divergence effect. During such conditions, radar echo maxima were thus produced on both lateral edges of the City and downwind of the city, while a minimum was located over the city itself.

The downwind maximum associated with moving convective storms is consistent with results from the classic METROMEX field study, which also showed a precipitation maximum downwind of St. Louis (Changnon, 1981). It is also consistent with the convective precipitation study of Selover (1997), which showed that moving summer convective storms over Phoenix, Arizona

* Corresponding author. Tel: + 1-408-924-5200; fax: + 1-408-924-5191.

E-mail address: pblmodel@sjsuvml.sjsu.edu (R. Bornstein)

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produce a precipitation minimum over the city in conjunction with surrounding lateral and downwind maximum values. The current analysis, however, only investigates effects of the Atlanta UHI on initiation of (and not of its impacts on moving) thunderstorms during a nine day summer period.

2. Data analysis

Data from the 42 sites in the Atlanta mesonet surface meteorological network (Hoogenboom, 1996) were available for the Olympics period from 26 July to 3 August 1996 in support of a modeling study for that period. Only 27 of those sites are within the analysis domain of Fig. 1. Of the remaining 15 sites, five are close enough to domain boundaries for inclusion in the analysis.

The mesonet sites provided data at 15-min intervals, starting on the hour. The end-time of each interval was used as the period identifier. Data from the eight NWS surface sites in the domain were also used. These data are collected once an hour, on the hour.

The term 'surface' applied to the above data refers to the standard WMO observational height of 1.5 m, except for the 10 m observational height of the wind velocity measurements. Potential temperature values were calculated from temperature values (using the PBL approximation) to remove elevation effects associated with topographic features. While the topography of the urban Atlanta region (Fig. 1) shows generally flat terrain (elevations between 200 and 300 m), a hill (up to about 700 m) exists north of the city.

The MATLAB software program plotted (at 15 min intervals) the combined observed mesonet and NWS surface meteorological data in the domain of Fig. 1. The inverse square weighting, spatial objective analysis scheme of Daley (1991) interpolated observed (or calculated) temperature, potential temperature, horizontal wind speed, and precipitation values onto a grid with a 5 km spacing. A five-point smoothing operator was used for 10 cycles (value determined by trial and error) for all parameters. Gridded wind speed values were then used to calculate Eulerian horizontal divergence fields. The MATLAB contour program then generated spatial

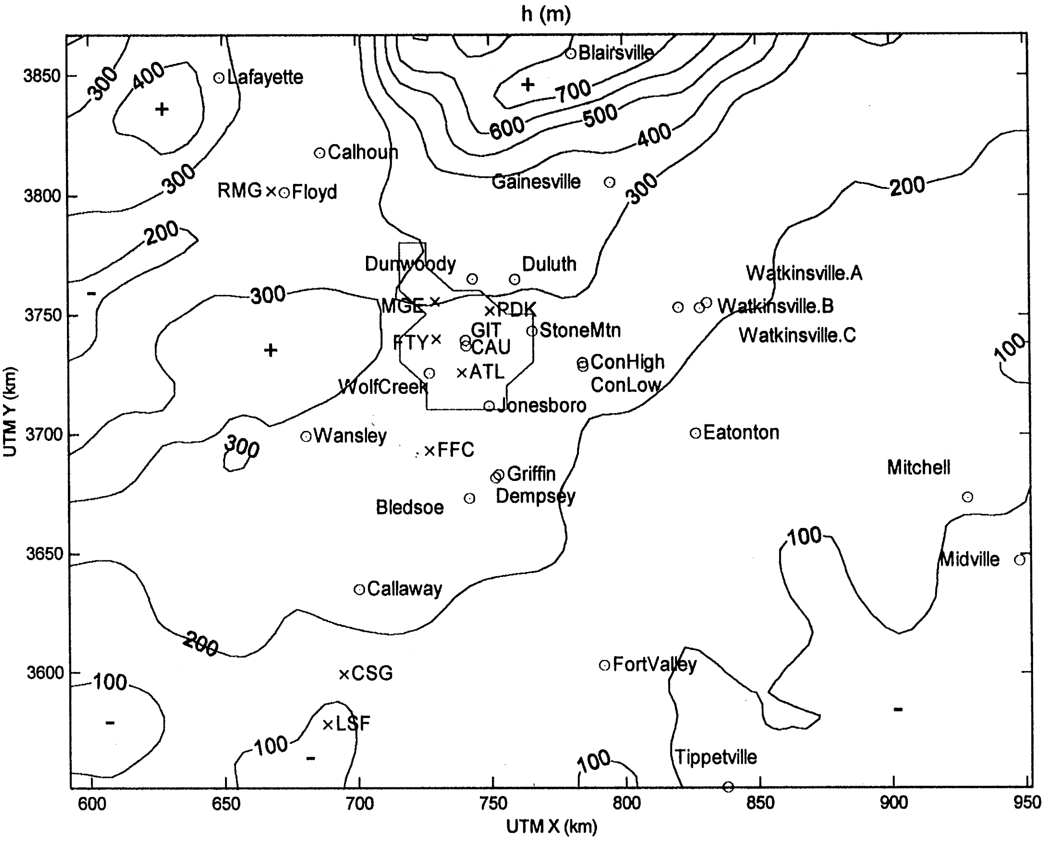

Fig. 1. Topographic height (100 m interval) analysis for Atlanta area. Also shown are mesonet sites (names), NWS sites (letter codes), and Atlanta boundary (geometric line).

distribution plots of each parameter. Details can be found in Lin (1999).

3. Results

A summary of the five urban influenced precipitation events found during the study period are shown in Table 1. Note that Eastern Daylight Savings time (EDT) is UTC minus 5 h; UHI values were determined from differences between temperatures at the center of Atlanta and in its coldest nearby environ; and convergence values are domain-wide (grid-point) maximia in $10^{-5}\ s^{-1}$. Maximum and total precipitation values are those associated with each storm, and do not necessarily represent urban values (see following section for case by case discussions). The sixth case appeared unrelated to urban influences (Lin, 1999).

At the start of some precipitation events, rain occurred at only one site (or at two sites, but for only one 15 min period). The periods of these events were not included in the following discussions or in the rain periods of Table 1.

Synoptic conditions shown on published NWS daily surface charts for most of the nine day period show a weak quasi-stationary or cold front over the southern US region, generally centered over Atlanta. A complete understanding of the two cases in which (cold front associated) synoptic scale precipitation systems were bifurcated requires the detailed satellite cloud analysis discussed in Lin (1999).

3.1. 26 July

In this case, the one partially described in Bornstein and Lin (1999), a generally weak daytime UHI center existed slightly northeast of Atlanta, due to the advection of heat from the city by a generally southwesterly (about $2.5\ m\ s^{-1}$) regional flow (Fig. 2). Maximum UHI values ranged from 2.0 to 2.5 K from 1200 to 1430 EDT, after which clouds were initiated. Cloud formation gradually weakened the UHI over the subsequent 2 h period, due to solar blockage.

While confluence over Atlanta can be seen in Fig. 2, the Eulerian divergence/convergence field (Fig. 3) was calculated from wind speed component values observed one hour later than those of Fig. 2. A regional component of the confluence can be seen in the predominantly northwesterly flow at all sites north in the northwest quadrant of the figure, versus the southwesterly flow at all sites south of Atlanta. The resulting east–west confluence zone coincides in time and space with the synoptic front mentioned above.

The strongest convergence of $10\times10^{-5}\ s^{-1}$ (largest value for any of the cases of Table 1) is found advected somewhat towards the downwind urban edge of Atlanta, with a somewhat weaker lobe extending southward. This entire area is part of a synoptic-scale frontal convergence zone that extends from west of the city, through the city, and up to the northeast domain corner. The precise maximum magnitudes at the western and northeastern ends of this convergence line are unknown, due to the relative data scarcity in those areas. It does, however, appear that UHI-induced convergence has been superimposed on the synoptic-scale convergence. Evidence for this superposition is found in the series of weak divergence maximia ringing the city, which form in the regions from which air is drawn away from the two background flows and subsequently into the Atlanta UHI. Note that the maximum divergence is located downwind of Atlanta (induced flow opposite to prevailing flow) and not on the lateral sides of the city (flows perpendicular) nor upwind of the city (flows in same direction).

Precipitation was initiated at 1445 EDT in the convergence lobe 25 km south (i.e., almost directly upwind) of the center of Atlanta (Fig. 3). The precipitation continued almost continuously until 2015 EDT, but its center moved slowly 40 km further upwind (i.e., to the southwest). The accumulation over the most intense precipitation period (1615–2000 EDT) shows a maximum value of

Table 1
Urban influenced storms, with precipitation characteristics and maximum values (and time) of: urban heat island (UHI); 15 minute and total precipitation; and convergence (C)

1996 Date	UHI (K)	*t* (EDT)	Precipitation (mm)				C ($10^{-5}\ s^{-1}$)	*t* (EDT)	Precipitation characteristics and storm movement
			15 min	*t* (EDT)	Total	*t* (EDT)			
26 July	2.5	1300	8.6	1615	15.8	1445–2015	10.0	1500	Urban initiated
27 July	3.0	0600	5.8	0900	10.2	0630–1100	2.5	0700	Synoptic-scale; urban bifurcation
30 July	4.0	0600	9.1	0630	9.6	0630–0930	5.5	0615	Urban initiated
31 July	5.0	0300	7.4	0345	16.8	0330–0530	8.5	0330	Synoptic-scale; urban bifurcation
3 August	5.0	0000	11.7	1030	37.1	0845–1200	4.5	0915	Urban initiated

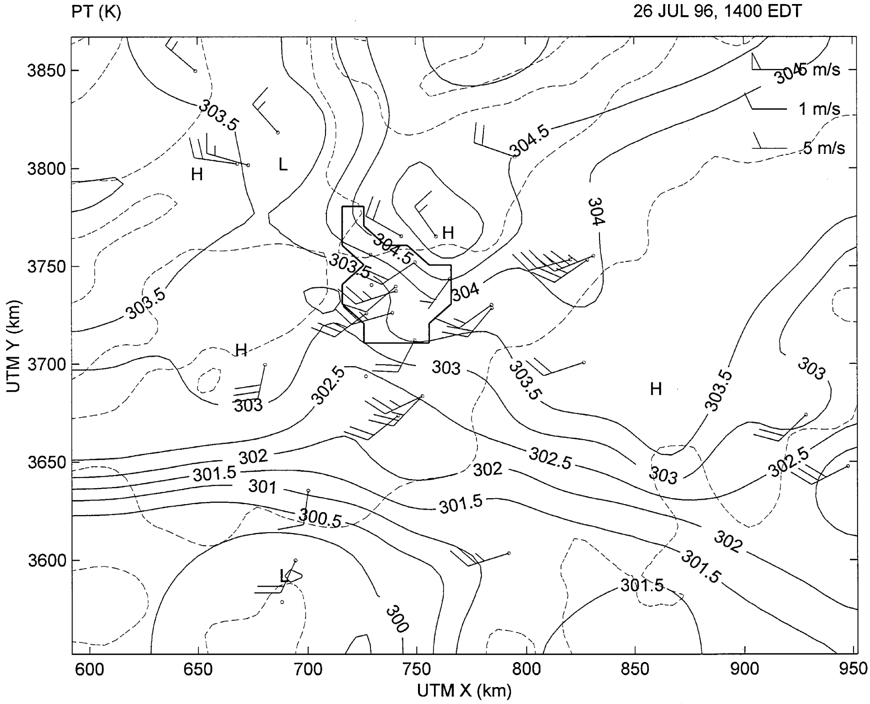

Fig. 2. Surface wind velocities (mesoscale speed scale in upper right) and potential temperature (solid lines, 0.5 K interval) analysis for Atlanta area at 1400 EDT on 26 July. Urban outline (dark line) and key topographic height contours (light dash lines) also appear in subsequent figures.

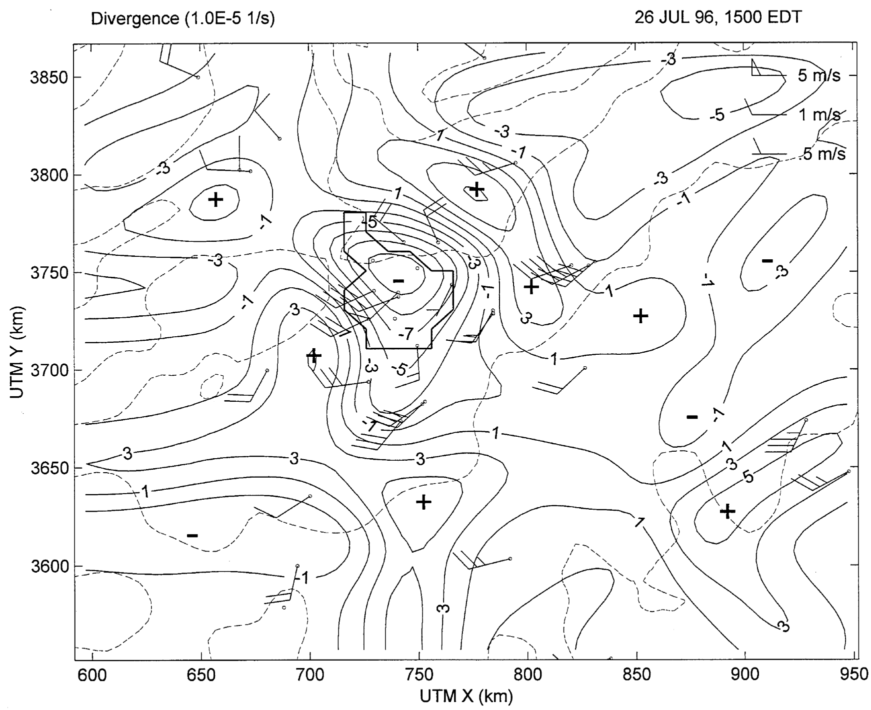

Fig. 3. Surface divergence (positive values)/convergence (negative values) analysis (increment of $2 \times 10^{-5}\ s^{-1}$) for Atlanta area at 1500 EDT on 26 July.

15.8 mm (Table 1) centered about 60 km south (i.e., generally upwind) of the center of Atlanta (Fig. 4).

3.2. 30 July

In this case, a clearly defined nighttime UHI was again centered directly over Atlanta in association with a very weak disorganized regional flow, upon which was imposed a moderate (up to 3.5 m s^{-1}) UHI-induced confluent flow (Fig. 5). UHI values ranged from 2.5 to 4.0 K, existed from 0000 to 0800 EDT, and showed a local maximum at 0600 EDT. Rain was then initiated at 0630 EDT over the city.

Confluence at 0600 EDT was centered somewhat downwind of the Atlanta urban center (Fig. 5), as a southwesterly background flow developed upwind of the city. Calculated convergence values (Fig. 6) thus show a downwind maximum over northeastern Atlanta of 5.5×10^{-5} s^{-1} at 0615 EDT. This nighttime convergence is stronger than that of the previous nighttime (not discussed 27 July bifurcation) case because of the now faster maximum urban winds. Note that while the convergence areas west and northeast of Atlanta look similar to those of 26 July, NWS surface charts did not show any fronts in the area.

Weak precipitation twice occurred (0430 and 0545 EDT), but for only 15 min periods at single sites outside the city. Stronger precipitation, however, was triggered at 0630 EDT at one site at the center of the urban convergence zone (Fig. 7). The rain lasted for 3 h, with a maximum accumulation of 9.6 mm (Table 1).

3.3. 3 August

In this case, a strong nighttime UHI (maximum value of 5.0 K at 0000 EDT) again existed over Atlanta and to the northeast (Fig. 8). This extension could be due to early morning slope solar heating, as this is the only case during this time period. It extended into the morning hours, with a secondary maximum of 3.0 K at 0900 EDT. A weak (2.5 m s^{-1}) northeasterly regional flow existed east-northeast of Atlanta, with confluent flow again over the city (at about 0.5 m s^{-1}). Rain was thus initiated at 0845 EDT upwind (i.e., east) of the city.

Regional confluence can be seen just south of Atlanta at 0815 EDT (Fig. 9) in association with the quasi-stationary cold front described above, although the frontal position was not likewise apparent in the temperature field of Fig. 8. Local confluence at 0800 and

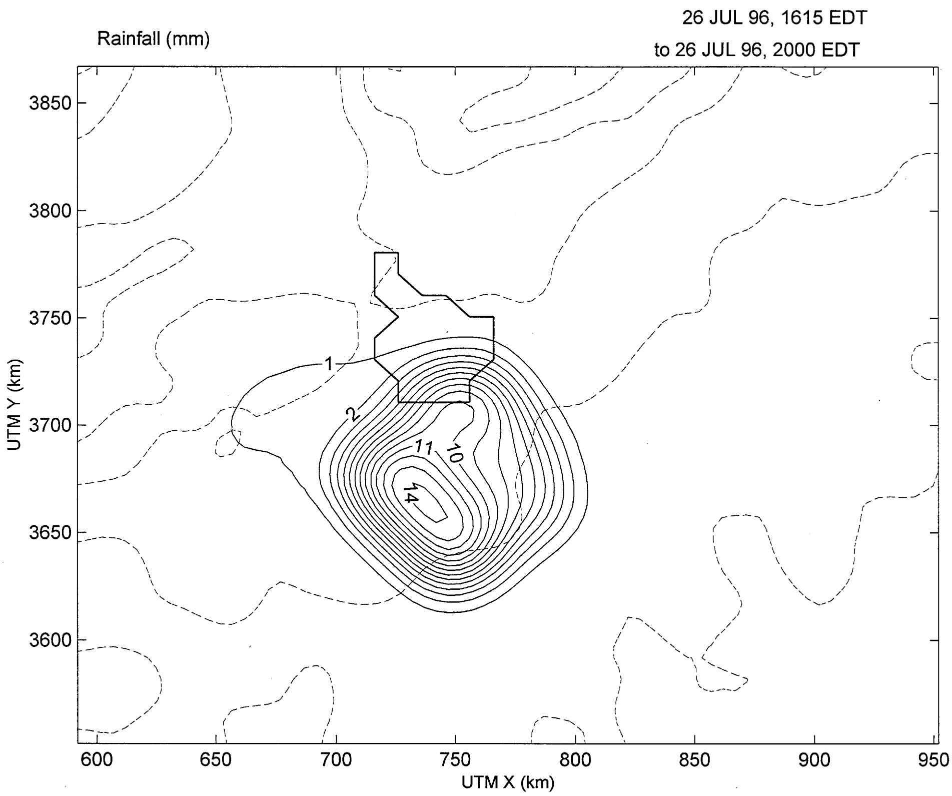

Fig. 4. Rainfall amount (increment of 1 mm) analysis for Atlanta area for 1615–2000 EDT on 26 July.

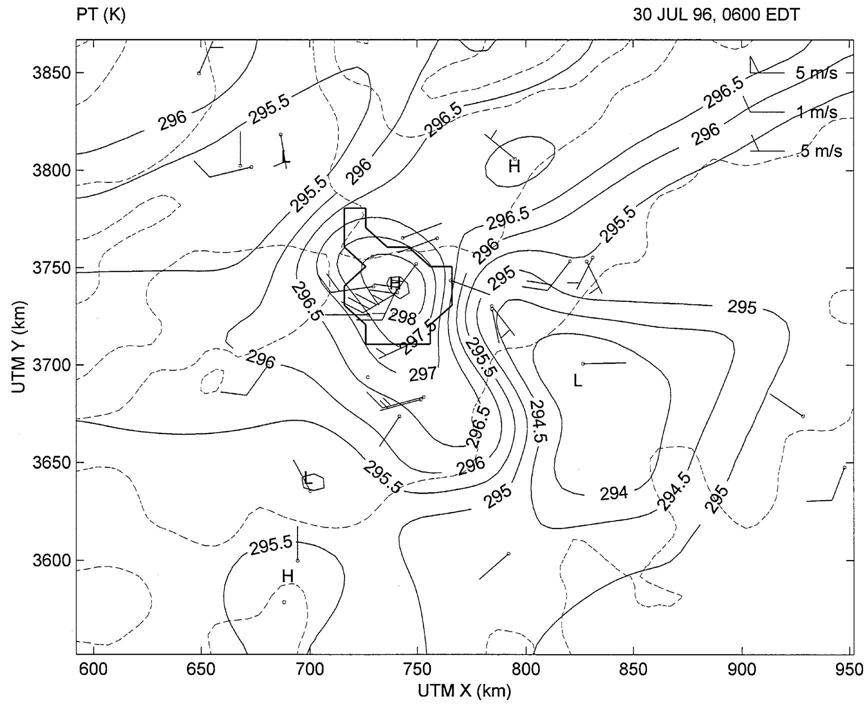

Fig. 5. Surface wind velocities and potential temperature (0.5 K interval) analysis for Atlanta area at 0600 EDT on 30 July.

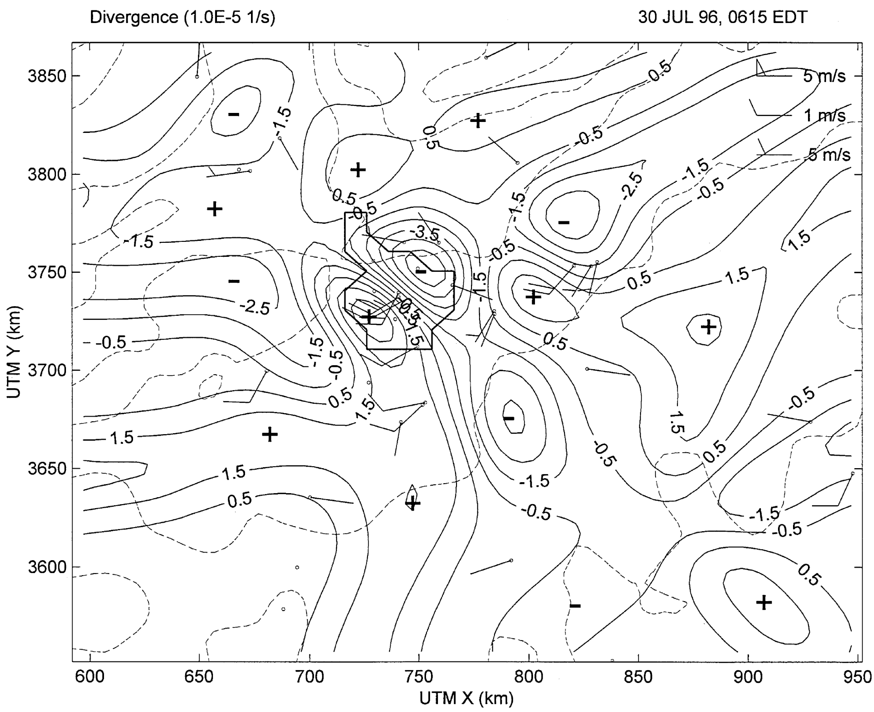

Fig. 6. Surface divergence (positive values)/convergence (negative values) analysis (increment of 10^{-5} s^{-1}) for Atlanta area at 0615 EDT on 30 July.

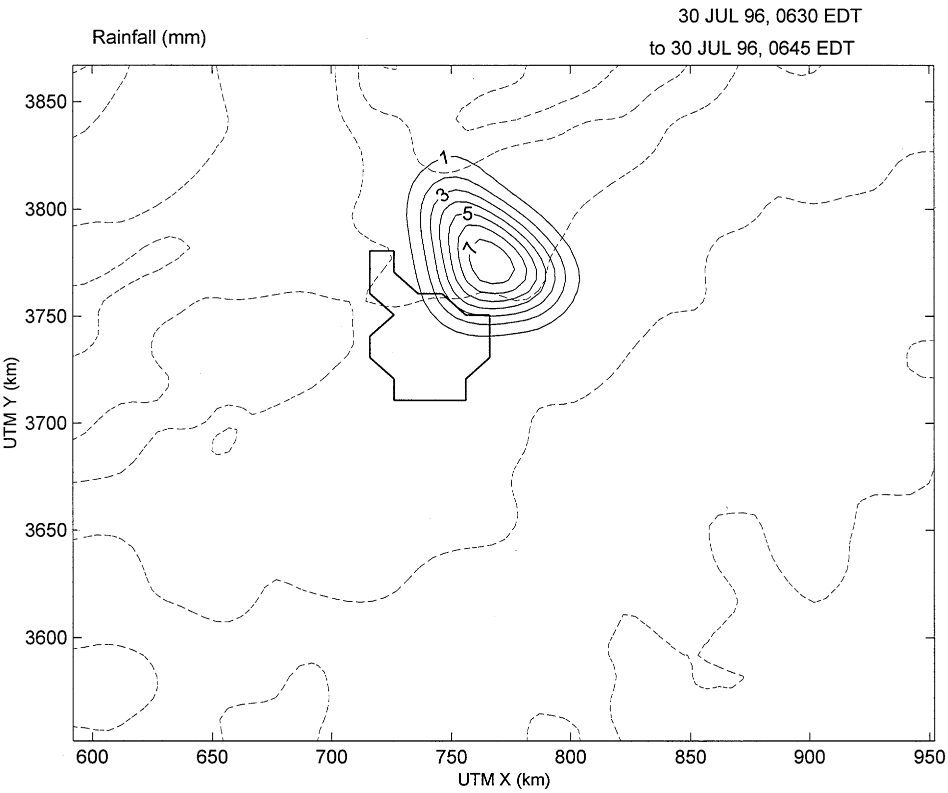

Fig. 7. Rainfall amount (increment of mm) analysis for Atlanta area for 0630–0645 EDT on 30 July.

0815 EDT over Atlanta can again also be seen, while moderate convergence ($2.5 \times 10^{-5}\ s^{-1}$ at 0815 EDT) was found 40 km down-wind (northeast) of Atlanta (Fig. 9). The urban-induced convergence area again seems ringed by divergence areas.

Precipitation was initiated at the downwind urban edge at 0945 EDT, concentrated over the city for about 1 h, and then advected downwind at 1045 EDT. Accumulation over the entire precipitation period (0945–1230 EDT) shows a maximum value of 22 mm centered on the eastern edge of Atlanta (Fig. 10).

4. Discussion

The above results showed a general agreement in time and space between the locations of maximum UHI, confluence, convergence, and precipitation values for all three urban-induced storms (Table 1). In particular, results showed the storms (at 0630, 0845, and 1445 EDT) were initiated in UHI-induced convergence zones. The afternoon event occurred during the normally most convective time of day. Note that this event had the minimum UHI (expected for daytime conditions), but the maximum convergence. Previous studies have shown that daytime UHI are more effective in producing vertical motions that those during nighttime stable conditions. Its only moderate precipitation accumulation is probably more related to moisture factors than to dynamical considerations.

While the 1.5 m UHI for the daytime case was centered somewhat downwind (northeast) of the city center, satellite observations have previously shown that daytime UHI values are maximum at the ground (and not at 1.5 m) in urban centers. The convergence zone on this day was hence located directly over the city center (and to the south), and the horizontal convergence was driven by unstable SBL vertical convective motions.

The other two initiated cases occurred before the establishment of unstable thermally convective SBL lapse rate conditions, and hence their convergence zones resulted from horizontal pressure gradient forces, which then forced (by mass conservation) the upward motions that produced the precipitation events. Since the maximum UHI in these two cases is displaced towards the eastern urban edge, the convergence center (and hence the precipitation center) is also likewise displaced.

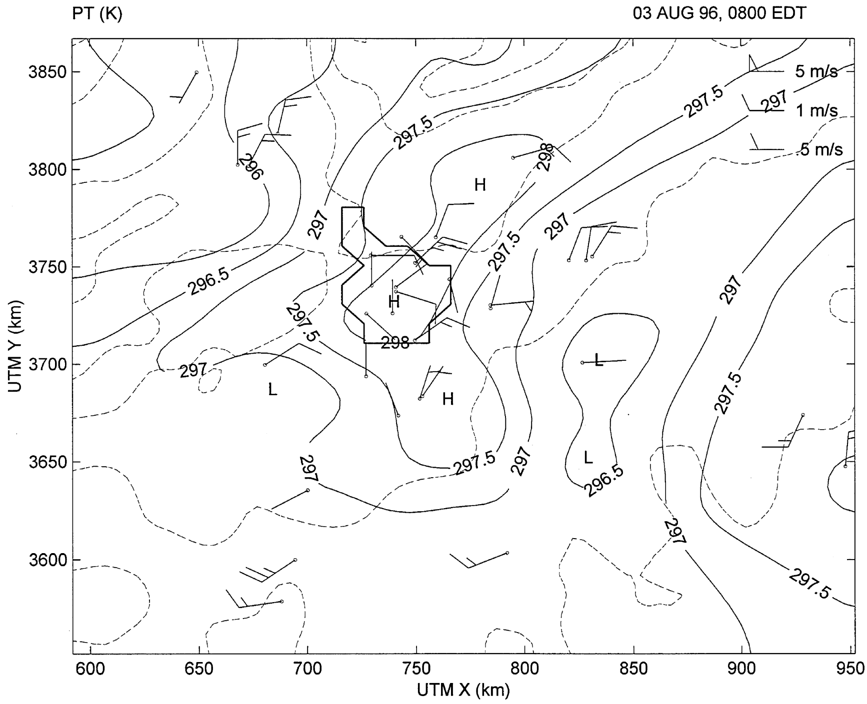

Fig. 8. Surface wind velocities and potential temperature (0.5 K interval) analysis for Atlanta area at 0800 EDT on 3 August.

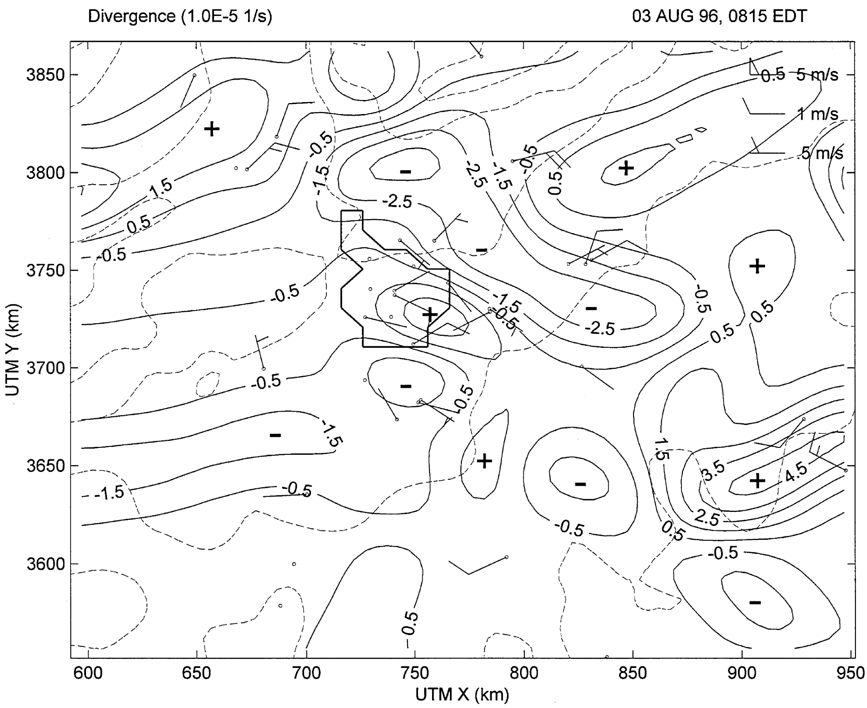

Fig. 9. Surface divergence (positive values)/convergence (negative values) analysis (increment of 10^{-5} s^{-1}) for Atlanta area at 0815 EDT on 3 August.

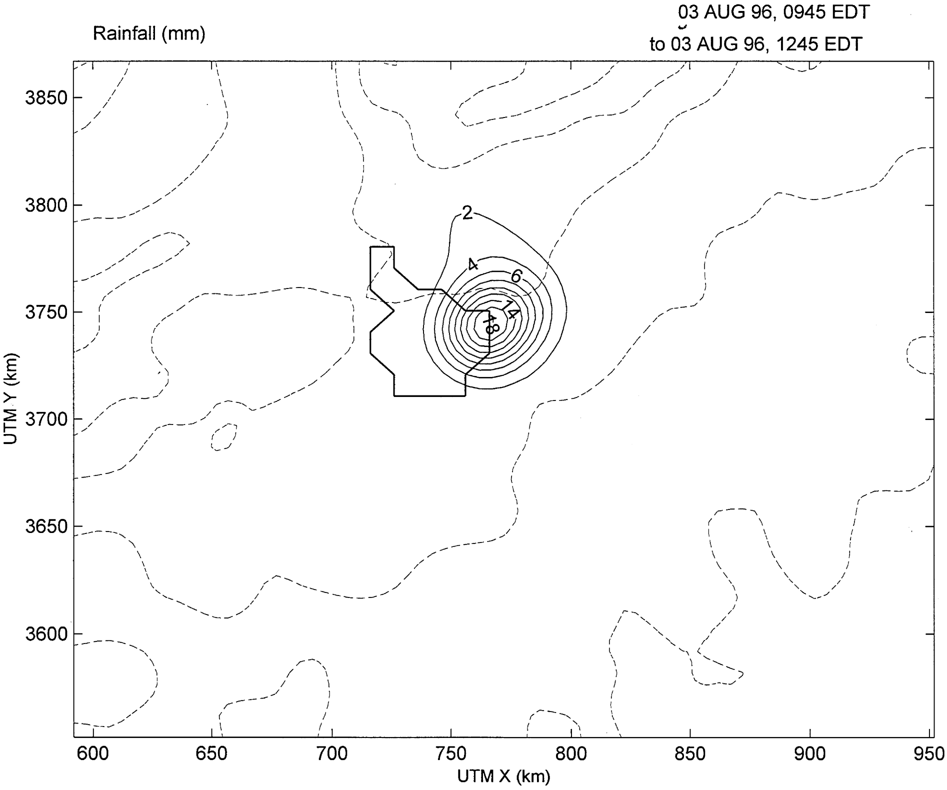

Fig. 10. Rainfall amount (increment of 2 mm) analysis for Atlanta area for 0945–1245 EDT on 3 August.

Note that on two (26 July and 3 August) of the three days, precipitation areas propagated upwind (relative to the direction of the surface wind). Such an effect was also noted in the METROMEX data (Changnon, 1981), and is probably due to upper level winds that could be associated with three-dimensional urban-induced flows.

Bornstein and LeRoy (1990) have previously shown that NYC effects either summer daytime thunderstorm formation or movement. They found initiation of convective activity over the UHI convergence zone in the NYC urban center during conditions with nearly calm regional flows. Thunderstorms moving with strong regional flows, however, tended to bifurcate and move around the city due to its building barrier effect.

The current Atlanta results thus agree with the NYC results with respect to thunderstorm initiation. Note that the NYC moving storms generally occurred during the late afternoon period, but that only one of the current Atlanta storms occurred during this period.

Note that the storm bifurcation identified in this study is different from storm splitting. The former implies that a group of storms move in two directions from a specific location (such as upwind of city). The latter implies that a single initial storm splits into two separated supercells, given appropriate vertical wind shear conditions.

One factor, however, complicates the current results, i.e., the regional convergence over the southeast US implied by the persistent quasi-stationary/cold front shown on NWS surface weather maps during the period. This regional convergence could have created regional low speed conditions, which then allowed for formation of both the mesoscale Atlanta UHI and its urban-induced convergence zone. Urban enhancement of regional convergence zones was found by McNider et al. (1998) as responsible for high ozone concentrations in southern US cities.

It is, however, possible that the regional convergence implied by the daily NWS surface weather maps was only an artifact of the few urban synoptic sites in the analyses, i.e., that the indicated synoptic front was only a line (sometimes contorted) through a series of independent local urban convergence zones. Mesoscale analyses of the regional synoptic data are needed to decide this question.

5. Conclusion

Six summer convective precipitation events over Atlanta during a nine day period in July–August 1996 were studied. Data from 40 mesonet and NWS sites were used in the analysis. Observed temperature and wind speed values were interpolated into gridded values, and then smoothed. Eulerian divergence values were calculated from the smoothed wind speeds, while potential temperature values were calculated from the smoothed temperature values to eliminate topographic effects on UHI values. Results showed a general agreement in time and space between the locations of maximum UHI, confluence, convergence, and precipitation values for the three storms found to be urban induced.

Future efforts should also involve analyses of climatological temperature and precipitation records from Atlanta to determine possible correlation between its changing UHI and precipitation fields. Such a study should follow the lead of METROMEX, and separately consider only one storm type moving in one direction.

The current mesoscale UHI, surface wind velocity, convergence, and precipitation analyses should be used to validate model simulations of convective thunderstorms over the Atlanta region. Given the difficulty in producing a convective thunderstorm at a time and place that matches an observed storm, one or more of the following strategies would need to be produce a base case for such a model exercise (in order of preference):

- carry out a series of simulations until one of them produces a thunderstorm at the observed time and place
- perturb the model at the appropriate (determined by trial and error) time and place to reproduce an observed thunderstorm
- simulate an idealized (but perturbed) thunderstorm case.

Urban and topographic influences on regional Atlanta temperature, transport, convergence, and precipitation patterns could be then evaluated by comparison of base-case results with those from additional simulations in which topographic and/or urban influences were sequentially eliminated.

Finally, results from these studies could be used to design a detailed field study to gather the data necessary to answer some of the (general and site-specific) questions related to urban effects on precipitation raised by the current study. Such a study should include a strong component of vertical measurement platforms, such as exists in the SCOS'97 study over the Los Angles basin. Such a study should include both summertime and wintertime storms.

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