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Effect of urbanization on the diurnal rainfall pattern in Houston

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Abstract:

Data from 19 raingauges located within and nearby Houston were analysed to quantify the impact of urbanization of the Houston metropolitan area on the local diurnal rainfall pattern. The average annual and warm-season diurnal rainfall patterns were determined for one time period when Houston was relatively small and likely would not have had a significant effect on meteorological processes (1940–58) and for a second, more recent, time period after Houston had become a major metropolitan area (1984–99). The diurnal rainfall patterns within the hypothesized urban-affected region and an upwind control region were compared for the pre- and post-urban time periods. Results indicated that the diurnal rainfall distribution in the urban area is much different than that found for the upwind and downwind adjacent regions for the 1984 to 1999 time period. For an average warm season from 1984 to 1999, the urban area and downwind urban-impacted region registered 59% and 30% respectively greater rainfall amounts from noon to midnight than an upwind control region. Moreover, the urban area had approximately 80% more recorded rainfall occurrences between noon and midnight during the warm season than surrounding areas. Comparison of the pre- and post-urban rainfall patterns indicated that the diurnal rainfall distribution has changed in southeast Texas. The changes are most significant in the urban area, especially for the afternoon time increments during the warm season. The average warm-season rainfall amount registered in the urban area increased by 25% from the pre- to the post-urban time period, while the amount in the upwind control region decreased by 8%. The majority of the increase was observed for the noon to 4 p.m. and 4 p.m. to 8 p.m. time increments. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS inadvertent weather modification; urbanization; diurnal rainfall distribution

INTRODUCTION

Urbanization alters the appearance of the natural landscape and perturbs Earth system processes. The hydrological cycle, in particular, is changed during construction as vegetation is removed, the soil layer is modified, and built structures and drainage infrastructure are introduced. In general, development activities within a watershed will reduce infiltration and groundwater recharge, increase surface runoff volumes and rates, reduce soil moisture, and modify the spatial distribution and magnitude of surface storage and fluxes of water and energy. The perturbed post-development hydrological processes can contribute to increased frequencies and magnitudes of nuisance and severe floods, accelerated geomorphologic changes to downstream waterways, and aquatic habitat impacts. Urban drainage controls are designed and constructed to mitigate hydrological impacts of development. Design procedures are based on providing adequate conveyance, infiltration, and/or storage capacity to control the modified surface runoff produced by rainstorms. The change in watershed characteristics between pre- and post-development is included in the design by performing the runoff calculations for post-development conditions. However, the change in the rainfall characteristics possibly caused by urbanization is not accounted for in the traditional design process, whereby the design storm is

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based on a statistical analysis of historical rainfall records. But, observational and modelling evidence has shown that major cities may indeed be influencing convective activity, causing modified precipitation patterns. If rainfall patterns are changing due to urbanization and the impacts to the hydrological drivers at the urban catchment scale are significant for flood control, stream geomorphology, and ecosystem response, then these changes should be factored into the design of urban drainage infrastructure.

Inadvertent rainfall modification by urban areas (UAs) has been studied extensively owing to its importance for weather prediction and modification, flood forecasting, hydrologic design, and water management. The topic is currently receiving renewed attention because previous research focused on a limited cross-section of cities and did not definitively identify the cause–effect relationship. A recently convened US Weather Research Panel recommended additional observational and modelling studies of the urban influence on rainfall (Dabberdt *et al*., 2000). More research is needed because the world's population continues to urbanize at an unprecedented rate and the implications of urbanization-induced local climate modification at the regional and global scales is not well understood. Moreover, the impact of local climate modification on the design and operation of engineered urban infrastructure systems is not well known and must be identified and quantified to develop appropriate mitigation protocols.

Early climatological investigations (e.g. Changnon, 1968; Landsberg, 1970; Huff and Changnon, 1972) found evidence of warm-season rainfall increases of 9–17% over and downwind of major cities. The Metropolitan Meteorological Experiment (METROMEX) was performed in St Louis (located in the Midwest USA) during the 1970s to investigate further the mesoscale and convective rainfall modification by major cities (Changnon *et al*., 1977). Increased precipitation amounts were observed within and 50–75 km downwind of the city, reflecting increases of 5–25% above background values (Changnon, 1979).

Numerous studies have validated and extended METROMEX over the past three decades. In a recent study, Shepherd *et al*. (2002) performed a unique analysis of rainfall rates measured by the precipitation radar (PR) aboard the Tropical Rainfall Measuring Mission (TRMM) satellite for the cities of Atlanta, Montgomery, Dallas, Waco, and San Antonio in the USA. They found that the average percentage increase in mean rainfall rate in the identified urban impact zone over an upwind control area was 28%. Recent numerical modelling studies have also demonstrated the effects of urban environments on the convective boundary layer and enhanced daytime thunderstorm formation (Bornstein and Lin, 2000; Thielen *et al*., 2000; Adegoke *et al*., 2001; Rozoff *et al*., 2003).

A couple of studies have investigated the effect of US UAs on the diurnal rainfall pattern. Huff and Vogel (1978) analysed the diurnal rainfall characteristics in the St Louis metropolitan area using data from the METROMEX network of 225 recording raingauges. Their analyses showed a major high in the urban-affected area during the later afternoon and early evening time period. During this diurnal peak period, both the rainfall frequency and rainfall amounts were greater in the urban-affected area. Further analyses suggested the enhancement was produced largely by greater rain amounts, rather than initiation of new rainstorms. Balling and Brazel (1987) analysed the long-term hourly rainfall record from the Phoenix (located in the southwest USA) airport raingauge to study the effect of urbanization on the local diurnal rainfall pattern. They found elevated rainfall amounts and slightly increased rainfall occurrences for summer months in the late afternoon and early evening for the time period 1970–85 compared with 1954–69. They also noted the decreased rainfall amounts and occurrences in the late forenoon period. They proposed urbanization and the unusual diurnal forcings of the Phoenix area to be responsible for the observed rainfall modification.

Although there is a rich collection of literature describing urban influences on rainfall, previous studies, via different approaches, reached conflicting understandings on urban area–rainfall relations. For instance, it is reported that UAs reduce rainfall due to cloud microphysics (Ramanathan *et al*., 2001), although many studies reviewed above showed that UAs enhance rainfall over and downwind of cities. The mechanisms of urban effects on rainfall are complex. On the one hand, cloud microphysics, in response to increased urban aerosols, may reduce rainfall, as suggested by Rosenfeld (1999). On the other hand, local dynamics and thermodynamics associated with an urban heat island (UHI)-induced convergence zone and a destabilized boundary layer may enhance urban rainfall (Shepherd *et al*., 2002; Changnon and Westcott, 2002; Ohashi and Kida, 2002). The synergistic effect of the elevated aerosols in UAs combined with the heat island and roughness may be suppressing or invigorating convective activity under specific conditions.

The objective of this paper is to extend the analysis of Shepherd and Burian (2003) by downscaling their rainfall data analysis in space and time to investigate the impact of urbanization on the diurnal rainfall pattern in Houston. In addition, the study seeks to corroborate the findings of Huff and Vogel (1978) and Balling and Brazel (1987) and demonstrate the urban effect on the diurnal rainfall distribution for a city with a hot, humid climate and near-coast geographic location. The next section describes the methods used in the data analysis, the third section presents the results and discussion, and the final section summarizes the most important results.

METHODS

Background

The primary hypothesis for the research presented in this paper is that the central Houston UA and the seasonally variant downwind regions (e.g. generally northeast for Houston, but northwest–northeast during the summer) exhibit a modified diurnal rainfall distribution relative to regions upwind of the city. Possible mechanisms for the urban-induced rainfall modification include one or a combination of the following: (1) enhanced convergence zone created by Houston UHI–sea breeze–Galveston Bay coastline interaction in a subtropical environment; (2) enhanced convergence due to increased surface roughness in the urban environment; (3) destabilization due to UHI-thermal perturbation of the boundary layer and resulting downstream translation of the UHI circulation or UHI-generated convective clouds; or (4) enhanced aerosols in Houston environment for cloud condensation nuclei sources. The mechanisms for the Houston urban rainfall anomaly will be further examined in future work. Here, the primary objective is to identify and quantify differences in the diurnal rainfall pattern between the Houston urban-affected region and an upwind control region (UCR) and to assess how these differences have changed from a pre-urban time period (1940–58) to a post-urban time period (1984–99).

Houston currently has a population of 1·9 million, ranking it as the fourth largest city in the USA. The Houston urbanized area, as defined by the US Census Bureau in 2000, has a population of 3·8 million, and the entire Houston–Galveston–Brazoria consolidated metropolitan statistical area (CMSA) has a population of 4·8 million. The Houston urbanized area encompasses approximately 3350 km^2 of the Gulf Coastal Plain with a high elevation of about 27 m above mean sea level. Houston's climate is subtropical humid, with very hot and humid summers and mild winters. In summer, the average maximum daytime temperature is 34 °C, and in winter the temperature averages between 4 and 16 °C. Humidity is greatest in the late summer and early fall, reaching a peak in October when levels can reach 93% at dawn. Average annual rainfall recorded at the Bush International Airport for the past two decades is 1200 mm. Analysis of thunderstorm day and rainfall amount data stratified by month suggests that rainfall during the summer months (June, July, and August) is dominated by sub-tropical convection, whereas spring and fall months (March, April, May, September, and October) contain a mixture of convective and frontal storms, and the winter months (November, December, January, and February) are dominated by frontal storms.

Previous investigations of urban effects on Houston rainfall have led to different conclusions, ranging from no effect to a significant effect. Kelly (1972) analysed 58 years of annual rainfall data from 22 raingauges distributed throughout southeast Texas to determine whether the data recorded by the Houston Weather Station were statistically different than the data from nearby rural gauges. Fourier analysis of that data indicated no significant difference between the rainfall trend at the Houston station, compared with the other stations. Additional analyses were performed on data from a 12-gauge Houston area rainfall network to determine monthly and annual spatial patterns for 1955–70. The spatial patterns did not reveal a discernible maximum over the UA. The rainfall patterns were also analysed in conjunction with data from the Houston air pollution monitoring network to determine whether increased air pollution was altering rainfall patterns. The analyses found no significant alteration of rainfall patterns due to air pollution.

Huff and Changnon (1973) studied weather records in eight US cities, including Houston, for indications of urban effects on rainfall. Their analyses of historical Houston weather data showed little evidence of an urban effect on monthly or seasonal rainfall patterns. However, a 17% increase in rainfall from non-frontal storms within the city during the warm season (June–August) from 1964 to 1968 was found relative to areas outside the city. Analyses of thunder days and hail days related to growth of the Houston industrial sector suggested a possible urban–industrial effect on thunderstorms in the area of industrial growth.

Data from 26 Houston-area raingauges for the time period 1901 to 1973 were analysed by Crooker and Goldman (1974). Annual precipitation isohyetals revealed significant precipitation modification along the axis of the mean annual near-surface wind direction. The modification was attributed to urban development. Bouvette *et al*. (1982) developed revised intensity–duration–frequency relationships for four Houston-area raingauges based on data up to 1981 and compared the revised intensities with those developed in 1961 by the US Weather Bureau. The 24 h, 100 year storm intensity had decreased by 13% from 1961 to 1981 for the downtown gauge, but had increased by an average of 15% for the three gauges in developing areas of the city.

A recent analysis of 12 years (1989–2000) of ground-based lightning data for the Houston area indicated that the highest flash densities recorded were over and downwind of the Houston area (Orville *et al*., 2001). Mesoscale model simulations suggested that the elevated lightning densities were caused by either UHI-induced convergence or enhanced lightning efficiency by increased urban aerosols, or some combination. Since lightning is associated with convection in the atmosphere, the urban modification of lightning patterns suggests that the UA is also impacting rainfall.

Shepherd and Burian (2003) used data from the world's first satellite-based PR aboard the TRMM and ground-based raingauges to quantify rainfall anomalies that were hypothesized to be linked to extensive urbanization in the Houston area. Analysis of 5 years of TRMM PR data showed a 28% (57%) increase in the mean rainfall rate in the downwind urban-impacted region (UIR) (UA) over a UCR. Burian and Shepherd (2004) analysed data dating from 1984 to 1997 from raingauges located within and nearby Houston. Raingauges in the urban-affected regions were found to have statistically significant higher average annual and warm-season rainfall amounts. The UA had 22% greater rainfall during the average warm season than the UCR and the downwind UIR. The isolated enhanced rainfall was consistent with the TRMM PR data analysis reported by Shepherd and Burian (2003). Further, to refine the identification of the urban effect on rainstorms in Houston, the raingauge data were divided into independent rain events and analysed for a relatively pre-urban time period (1940–58) and a post-urban time period (1984–99) for nine raingauges. The average maximum 1 h intensity during the warm season increased from the pre- to post-urban time period in the UA by 16%, compared with a 4% increase in the UCR. More convincing evidence was noted for the average number of 'heavy' ($\geq$25 mm) rainstorms occurring during the warm season, which increased by 35% in the urban-affected region from the pre- to post-urban time period, whereas a 3% decrease was noted in the UCR.

Reference coordinate system

The diurnal rainfall analyses reported in this paper used the theoretical coordinate system defined for Houston by Shepherd and Burian (2003), following the procedures set forth by Shepherd *et al*. (2002). The coordinate system is centred on the Houston urban core area, which is approximately 80 km inland from the Gulf of Mexico. The prevailing near-surface wind flow is predominantly southeasterly, driven by the sea breeze. The 700 hPa level was chosen as a representative level for the mean steering flow for convective storms and is supported by previous work in the literature (e.g. Hagemeyer, 1991). Wind direction data covering the years 1979–98 from the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis dataset (Kalnay *et al*., 1996) was used to determine the mean annual and seasonal 'prevailing' flow at 700 hPa for Houston. For each season, the reference coordinate system is oriented according to the mean prevailing wind direction. The mean annual 700 hPa prevailing wind direction was found to be 230° (southwesterly) and the mean warm season (June–August) wind direction was 178° (southerly; see Figure 1). Previously observed rainfall anomalies in other cities have been found 50–100 km downwind of the urban centre. Therefore, for the annual coordinate system the UIR was extended approximately 150 km from the northeastern edge of the UA in the seasonal downwind direction to ensure capture of rainfall anomalies. The UCR extends an equal distance upwind of the southwestern edge of the UA. The UIR includes a 125° sector to account for the variability of the wind direction. The warm-season coordinate system was developed similarly using the mean warm-season wind vector as the reference axis. Further details about the derivation of the reference coordinate system for Houston can be found in Shepherd and Burian (2003). The raingauge data within the UCR, UA, and UIR as defined by the reference coordinate systems were processed to determine average annual and warm-season diurnal rainfall patterns in the three regions.

Diurnal rainfall patterns

The average annual and average warm-season diurnal rainfall patterns were determined by analysing the data from raingauges located within and nearby the Houston metropolitan area. All raingauge records archived by the National Climatic Data Center (NCDC) for the hourly and 15 min stations within a 250 km radius of downtown Houston were initially selected for analysis. After initial extraction, 53 gauges were available for further screening. The objective of this study was to investigate the impacts of urbanization on the diurnal rainfall pattern. To meet this objective, rainfall records are required for two time periods: one when the urban-affected area was relatively rural and the other when the area was highly urbanized. The 'pre-urban' time period was chosen to be 1940–58 and the 'post-urban' time period was selected to be 1984–99. In 1940, the Houston metropolitan area had a population of less than 650 000 and the post-World War II expansion had not yet begun. In 1984, the population of the metropolitan area was more than 3 million and contained a major industrial component. During the 1990s, the growth of the Houston area was rapid, and now the current metropolitan population is greater than 4·4 million. Most of the population before 1958 was within the city limits, but the urban sprawl dynamic has shifted the majority of the population (and urban surface area) of the metropolitan area outside of the Houston city limits during the second half of the 20th century. The larger urbanized land area rather than increased population density likely has a greater effect on meteorological

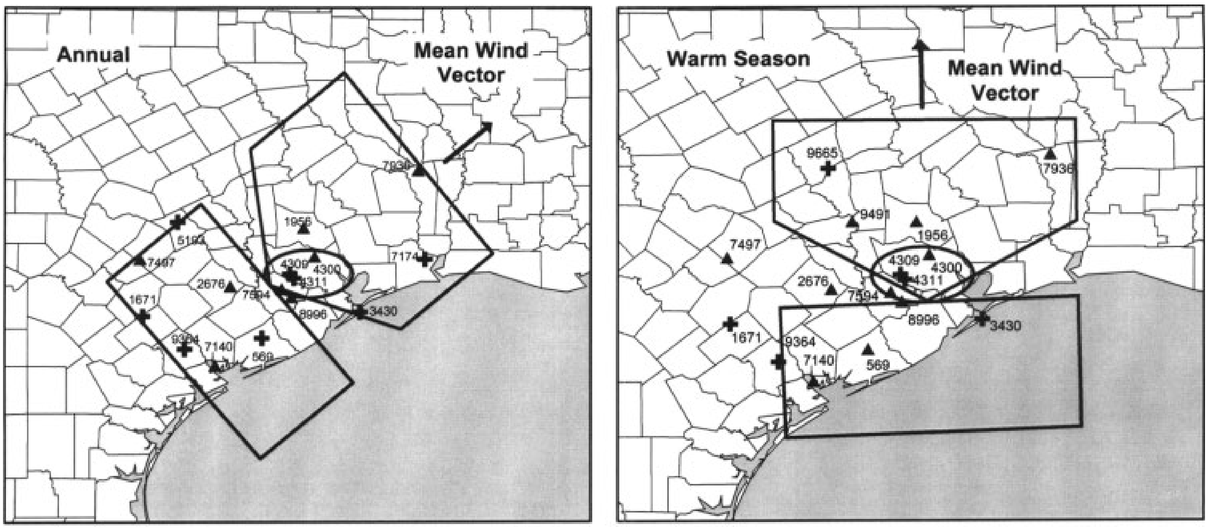

Figure 1. Analysis coordinate system for mean annual (230°) and mean warm-season (178°) reference wind directions at 700 hPa. Raingauges included in the analysis are shown as a cross if they have data for both the pre- and post-urban time period; raingauges shown as triangles only have post-urban time period data

processes. Therefore, the urban influence on rainfall, if present, is expected to be much less during the pre-urban time period than the post-urban time period. Owing to natural background climate variability, comparing the pre-urban and post-urban time periods for each raingauge or for averages of raingauges in each zone might not provide useful information. Rather, we are interested in comparing the changes of rainfall characteristics in the urban area from pre-urban to post-urban relative to the changes observed in the UCR. The hypothesis is that if the urban effect is present the more significant diurnal rainfall pattern changes will be observed in the UA and UIR compared with the UCR. To analyse the pre-urban time period, the mean 700 hPa prevailing wind directions found for 1979 to 1998 were assumed to be representative of the prevailing wind directions for 1940 to 1958.

The raingauges used in this part of the study had to have less than 10% of total data missing from the two periods (1940–58 and 1984–99) and had to be in hourly, or less, time increments (i.e. daily records were not included). A year of record would be excluded if more than one continuous month of data was missing and recorded hurricane and tropical storm events were removed from the records. Of the 53 raingauges originally extracted from the NCDC archives, only 19 had sufficient coverage for the post-urban time period, and only nine had sufficient data for both the pre- and post-urban time periods (see Figure 1). The mean wind-flow coordinate system contained 16 of the 19 gauges (seven in the UCR, five in the UA, and four in the UIR), whereas the warm-season coordinate system contained a slightly different set of 16 gauges from the 19 available (seven in the UCR, five in the UA, and four in the UIR). These data were used to compare the UCR, UA, and UIR for the post-urban time period only. Of the nine gauges with adequate pre- and post-urban data coverage, two are within the UA, two are within the UIR, and four are within the UCR for the annual mean wind flow, and two are within the UA, one is within the UIR, and three are within the UCR for the warm-season mean wind flow.

To study the diurnal rainfall distribution, the day was divided into 4 h time increments starting at midnight local time (Central Standard Time): midnight to 4 a.m., 4 a.m. to 8 a.m., and so on. Before analysing the rainfall frequency and amount in each time increment, a final rain-record processing step had to be performed to distribute the accumulated values in the NCDC records evenly over the accumulated time period. This step has a negligible effect on the diurnal analysis, because the duration of accumulations is a small fraction of the overall record duration for all records used. The rainfall records were then analysed within the UCR, UA, and UIR for both the pre-urban time period (1940–58) and the post-urban time period (1984–99), with the number of occurrences of rain and the amount of rain being summed in each time increment.

RESULTS

Post-urban time period

Plots were constructed for individual raingauges and for the three analysis zones (UIR, UA, and UCR) showing the percentage of the average daily rainfall in each 4 h time increment. The plot of the average diurnal distributions of gauges in the UA, UIR, and UCR is shown as the top part of Figure 2. For all three zones the average diurnal distribution is similar, with higher fractions of the total rainfall during the afternoon (hours 12–16) and the early evening (hours 16–20) time increments. A diurnal rainfall distribution with a higher fraction of the average daily rainfall in the afternoon and early evening is representative of a large part of the USA. However, note the relatively higher fraction of average daily rainfall occurring during the 12–16 and 16–20 time increments in the UA compared with the other two regions. For the 12–16 time increment the UA fraction of average daily rainfall is greater than the UIR and UCR by 18% and 26% respectively. Thus, on average, throughout the year the UA receives a higher fraction of average daily rainfall during the afternoon and early evening compared with *both* upwind and downwind areas. The rainfall anomaly noted in the UA in the afternoon and early evening may be linked to the UHI in Houston during the warm season, as other researchers have suggested (e.g. Orville *et al*., 2001; Shepherd and Burian, 2003). The bottom part of Figure 2 shows the average diurnal distributions during the warm season (June, July, and August). Similar to

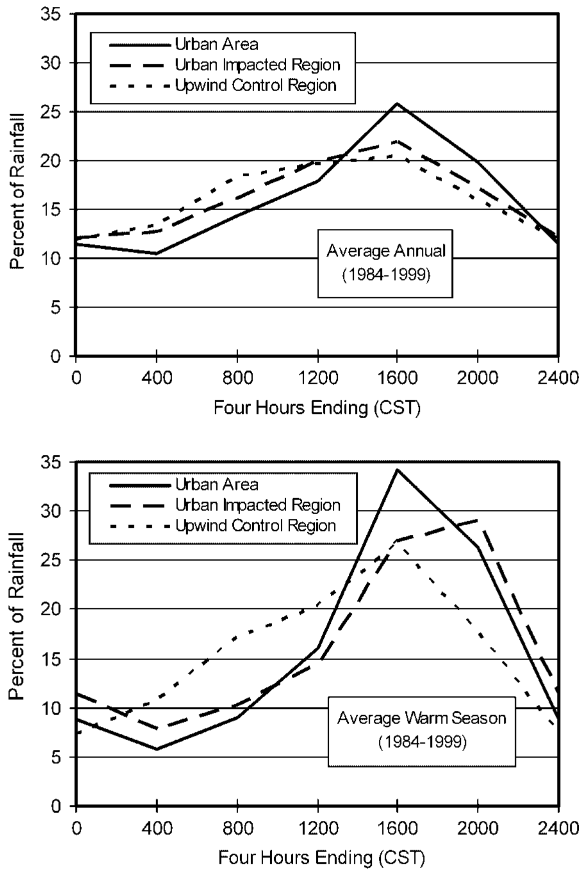

Figure 2. Average annual (top plot) and warm-season (bottom plot) diurnal distributions of rainfall amount for the UA, UIR, and UCR. Data for raingauges within each area are averaged for the time period 1984 to 1999

the annual distribution, the UA has a 26% and 28% higher fraction of rainfall occurring during the 12–16 time increment compared with the UIR and UCR respectively.

To focus further on the warm season, a plot was prepared comparing the diurnal distribution of a representative UA gauge and a representative UCR gauge. Figure 3 compares the warm-season diurnal rainfall distribution for a gauge located in the UA (Station No. 4311) and a gauge located in the UCR (Station No. 7140). The UCR gauge 7140 is located less than 80 km southwest of the UA gauge 4311 at about the same distance inland from the Gulf of Mexico and also located near a large embayment. On average, gauge 4311 registered 24% more rainfall from 1984–99 than did gauge 7140. The diurnal distribution was significantly altered, with 79% and 88% more rainfall respectively during the 12–16 and 16–20 time increments for the UA gauge than the UCR gauge. During the warm season, the UA gauge 4311 registered, on average, 34% more rainfall from 1984 to 1999 than UCR gauge 7140. The warm-season 12–16 and 16–20 time increments registered 85% and 131% respectively more rainfall at UA gauge 4311 than UCR gauge 7140.

Table I compares the average annual amount of rainfall in each time increment for the gauges located in the UA, UIR, and UCR. The UA registers slightly less rainfall during the 0–4 and 4–8 time increments, but recorded much more rainfall during the 12–16 and 16–20 time increments compared with the UCR. The UIR registers more rainfall than the UCR for all time increments. The increased rainfall in the UIR compared with the UCR may be caused by an increasing rainfall gradient from southwest to northeast. However, the higher increases in afternoon and early evening rainfall in the UA compared with the UIR suggest that if a rainfall

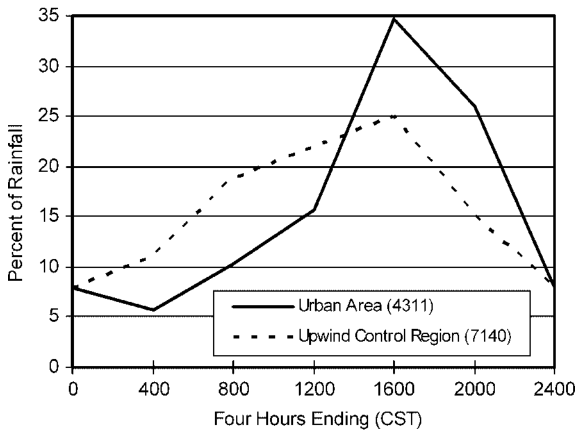

Figure 3. Comparison of average warm-season diurnal rainfall distribution for one raingauge in the UA (4311) and one in the UCR (7140)

Table I. Average annual rainfall amount (mm) during each 4 h increment from 1984 to 1999

	UA	UIR	UCR	Change between UA and UCR (%)	Change between UIR and UCR (%)
0–4	118	161	121	−3	+33
4–8	162	199	168	−4	+19
8–12	202	249	181	+12	+38
12–16	291	273	187	+56	+46
16–20	225	216	146	+54	+48
20–24	129	150	108	+19	+39
Total	1127	1248	911	+24	+37

Table II. Average warm-season rainfall amount (mm) during each 4 h increment from 1984 to 1999

	UA	UIR	UCR	Change between UA and UCR (%)	Change between UIR and UCR (%)
0–4	15	17	24	−38	−30
4–8	24	22	38	−37	−42
8–12	42	32	45	−7	−29
12–16	90	61	60	+50	+2
16–20	70	65	39	+80	+67
20–24	23	24	16	+44	+50
Total	264	221	222	+19	0

gradient is present then it is being perturbed in the afternoon time increments in the UA. Table II compares the average warm-season (June, July, August) amount of rainfall in each time increment. Similar to the annual diurnal distribution, less rainfall is recorded in the UA and UIR than the UCR for the morning increments (0–4, 4–8, and 8–12), but the differences are much greater for the warm season. During the afternoon and evening time increments the UA and UIR experience much greater rainfall amounts during the warm season, with the UA receiving the greatest.

The altered diurnal distribution of rainfall amount suggests that rainfall is most enhanced in the UA during the afternoon increment 12–16, early evening increment 16–20, and late evening increment 20–24. The UIR experiences enhanced rainfall predominantly in the 16–20 and 20–24 time increments compared with the UCR. From noon to midnight the UA and UIR received, on average, 45% more rainfall from 1984 to 1999 than the UCR. During the warm season, the noon-to-midnight rainfall amount is 59% and 30% greater in the UA and UIR respectively than the UCR.

Table III lists the average annual diurnal distribution of rainfall occurrences. On average, there were 44% and 43% more rainfall occurrences in the UA and UIR respectively than in the UCR each year from 1984 to 1999. The diurnal distribution differences noted in the rainfall amounts are again apparent, with the much higher increases in number of rainfall occurrences during the 12–16, 16–20, and 20–24 time increments. A southwest-to-northeast rainfall-occurrence gradient is not present. Table IV shows the average warm-season rainfall occurrences from 1984 to 1999. A strong diurnal difference between the UA and the UCR is present, and a smaller difference between the UIR and UCR. Especially evident are the large increases in rainfall occurrences in the afternoon and evening time increments in the UA compared with both the UIR and UCR, suggesting a localized effect within the UA. From the noon-to-midnight time period the UA registered 79% more rainfall occurrences than the UCR, whereas the UIR registered only 6% more occurrences.

Comparison of pre- and post-urban time periods

The top part of Figure 4 shows the average diurnal rainfall distribution during the warm season for both the pre- and post-urban time periods for gauge 4311 located in the UA. Visual inspection of Figure 4 indicates that the diurnal rainfall distribution has shifted for this gauge, such that a higher fraction of rain falls during the 12–16 time increment for the 1984–1999 time period than the 1940–1958 time period. The bottom part of Figure 4 shows that the warm-season diurnal distribution for gauge 4311 and the increased fraction of daily rainfall in the 12–16 and 16–20 time increments is more pronounced. To confirm the observation from gauge 4311, plots were also constructed (not shown here) for the other UA raingauge (4309), and the resulting

Table III. Average annual number of rainfall occurrences during each 4 h increment from 1984 to 1999

	UA	UIR	UCR	Change between UA and UCR (%)	Change between UIR and UCR (%)
0–4	26	25	18	+46	+42
4–8	25	29	22	+15	+36
8–12	29	34	25	+17	+35
12–16	40	36	26	+54	+42
16–20	35	32	20	+73	+57
20–24	26	24	15	+68	+53
Total	181	180	126	+44	+43

Table IV. Average warm-season number of rainfall occurrences during each 4 h increment from 1984 to 1999

	UA	UIR	UCR	Change between UA and UCR (%)	Change between UIR and UCR (%)
0–4	3·4	1·5	3·3	+3	−55
4–8	3·4	2·5	4·8	−29	−48
8–12	5·9	3·9	6·4	−8	−39
12–16	11·9	6·6	7·5	+59	−12
16–20	9·9	6·5	4·8	+106	+35
20–24	4·7	2·7	2·6	+81	+4
Total	39·2	23·7	29·4	+33	−19

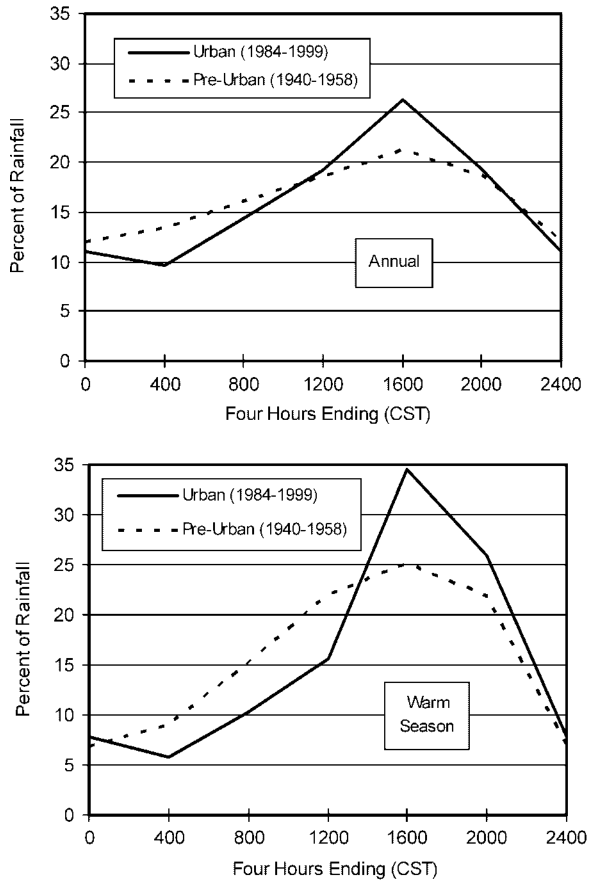

Figure 4. Comparison of average annual (top plot) and warm-season (bottom plot) diurnal rainfall distribution at gauge 4311 in the UA for the pre- and post-urban time periods

change in pattern from pre- to post-urban is similar. The higher fraction of average daily rainfall occurring during the afternoon provides additional support that the UHI is a contributing factor to the warm-season rainfall differences observed in the UA and UIR compared with the UCR.

The pre- and post-urban diurnal distribution plots for gauges in the UCR were also created to determine whether the diurnal pattern was modified similarly from pre- to post-urban in the UCR. Figure 5 shows the average distributions for the annual and warm-season fractions of average daily rainfall for the gauges in the UCR. Visual inspection indicates that the UCR gauges do not have a significantly altered diurnal distribution in terms of increased fraction of average daily rainfall in the afternoon time increments. Instead, a shift in peak of the fraction of the average daily rainfall is noticed for the warm season, moving from the 8–12 to the 12–16 time increment. Therefore, the UCR gauges do experience some changes, but the changes are not of the magnitude observed for the UA gauges.

Table V compares the average annual rainfall amount falling in each time increment in the UA, UIR, and UCR for the pre- and post-urban time periods. Background climate variation from the pre- to post-urban time periods may exist for southeast Texas; consequently, the comparison of the rainfall amounts from one time period to another must be based on relative changes (i.e. if the urban-affected areas experience greater change than the upwind control area then the enhanced change in the urban area may be an urban-induced phenomenon). The data display the same general pattern, with small increases of average annual rainfall

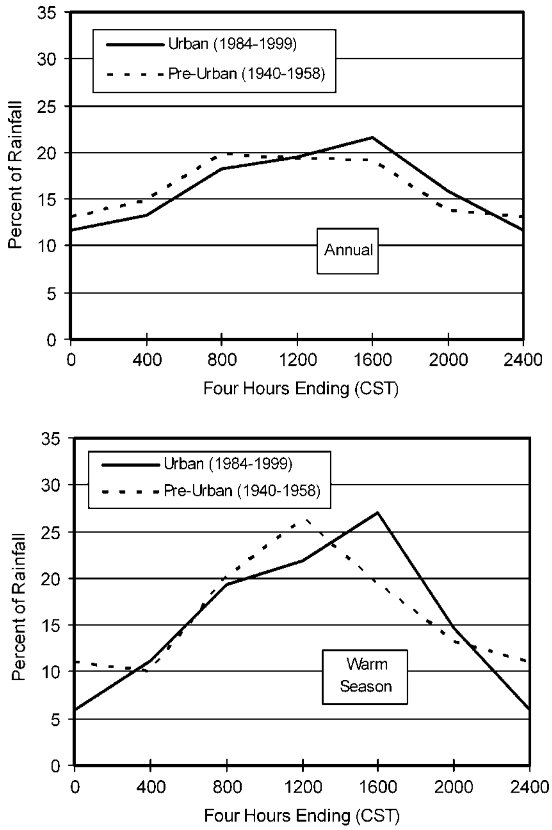

Figure 5. Comparison of average annual (top plot) and warm-season (bottom plot) diurnal rainfall distribution for the average of the UCR gauges for the pre- and post-urban time periods

Table V. Average annual rainfall amount (mm) during each 4 h increment from 1940 to 1958 and from 1984 to 1999

	UA[a]			UIR[b]			UCR[c]		
	1940–58	1984–99	Change (%)	1940–58	1984–99	Change (%)	1940–58	1984–99	Change (%)
0–4	137	113	−18	150	182	+21	126	123	−2
4–8	163	158	−3	219	226	+3	170	170	0
8–12	185	218	+18	254	267	+5	164	183	+12
12–16	209	301	+44	212	265	+25	162	203	+25
16–20	179	236	+32	170	195	+15	115	148	+29
20–24	134	124	−8	134	158	+18	109	107	−2
Total	1007	1150	+15	1139	1293	+14	846	934	+10

[a] Average of gauges 4311 and 4309.
[b] Average of gauges 7174 and 3430.
[c] Average of gauges 1671, 5193, 569, 9364.

and rather large increases in rainfall during the 12–16 and 16–20 time increments. Although the patterns of change noted for the UA, UIR, and UCR are similar, the magnitude of change is significantly greater in the UA for the 12–16 time increment (+44% compared with +25%). The difference in change between the UA and the other regions is even more pronounced when the time increment values are normalized by average

Table VI. Average annual fraction (%) of daily rainfall during each 4 h increment from 1940 to 1958 and from 1984 to 1999

	UA[a]			UIR[b]			UCR[c]		
	1940–58	1984–99	Change (%)	1940–58	1984–99	Change (%)	1940–58	1984–99	Change (%)
0–4	13·6	9·8	−28	13·3	14·1	+6	14·8	13·3	−10
4–8	16·1	13·7	−15	19·4	18·0	−7	19·9	18·2	−9
8–12	18·4	19·0	+3	22·4	20·7	−8	19·3	19·4	+1
12–16	20·7	26·1	+26	18·5	20·0	+8	19·1	21·5	+13
16–20	17·8	20·5	+15	14·7	14·8	+1	13·8	15·9	+15
20–24	13·4	10·9	−19	11·7	12·4	+6	13·1	11·7	−11

[a] Average of gauges 4311 and 4309.
[b] Average of gauges 7174 and 3430.
[c] Average of gauges 1671, 5193, 569, 9364.

Table VII. Average warm-season rainfall amount (mm) during each 4 h increment from 1940 to 1958 and from 1984 to 1999

	UA[a]			UIR[b]			UCR[c]		
	1940–58	1984–99	Change (%)	1940–58	1984–99	Change (%)	1940–58	1984–99	Change (%)
0–4	17·9	14·5	−19	—	—	—	25·2	25·3	0
4–8	37·4	25·9	−31	—	—	—	50·3	43·7	−13
8–12	45·3	43·8	−3	—	—	—	66·8	49·7	−26
12–16	58·1	95·1	+64	—	—	—	47·1	61·6	+31
16–20	47·9	79·1	+65	—	—	—	31·3	33·3	+6
20–24	17·7	21·8	+23	—	—	—	25·8	13·2	−49
Total	224	280	+25	—	—	—	247	227	−8

[a] Average of gauges 4311 and 4309.
[b] UIR gauges had insufficient data for warm-season analysis.
[c] Average of gauges 1671, 3430, 9364.

daily rainfall amount, as shown in Table VI. The change observed in the UA from pre- to post-urban is twice as much as that observed in the UIR and UCR for the 12–16 time increment.

Table VII compares the average warm-season rainfall amount falling in each time increment within the UA, UIR, and UCR for the pre- and post-urban time periods. For the warm season pre- versus post-urban comparisons the UIR data were insufficient to provide meaningful results. The UA and the UCR both experienced changes to the diurnal rainfall pattern; but, as was found for the annual average pattern, the changes in the UA are much more significant. The difference is more noticeable for the 12–16 and 16–20 time increments, where the UA experienced a change of at least twice the magnitude of the change in the UCR. Overall, the UA had a 25% greater rainfall amount during the warm season for the post-urban time period than the pre-urban time period, whereas the UCR experienced a net reduction of 8%. The values for the average fraction of daily rainfall in each time increment for the warm season are shown in Table VIII. The normalized values in Table VIII indicate that both areas have experienced significant diurnal rainfall pattern changes with time.

Figure 6 shows the magnitudes of difference (and percentage differences) between the average warm-season rainfall amount recorded in the UA and UCR for each time increment for the pre- and post-urban time periods. For example, for the 12–16 time increment the pre-urban difference between the rainfall amount recorded in the UA and UCR is +11 mm, or +23%. Overall, the UCR had 9% more recorded average warm-season rain than the UA in the pre-urban time period. In the post-urban time period the UA had 24% more average

Table VIII. Average warm-season fraction (%) of daily rainfall during each 4 h increment from 1940 to 1958 and from 1984 to 1999

	UA[a]			UIR[b]			UCR[c]		
	1940–58	1984–99	Change (%)	1940–58	1984–99	Change (%)	1940–58	1984–99	Change (%)
0–4	7·8	5·2	−33	—	—	—	10·0	11·1	+11
4–8	16·9	9·2	−46	—	—	—	20·1	19·4	−3
8–12	19·9	15·6	−22	—	—	—	26·3	21·8	−17
12–16	26·0	34·0	+31	—	—	—	19·3	27·0	+40
16–20	21·3	28·3	+33	—	—	—	13·3	14·8	+11
20–24	8·1	7·7	−5	—	—	—	11·0	5·9	−46

[a] Average of gauges 4311 and 4309.
[b] UIR gauges had insufficient data for warm-season analysis.
[c] Average of gauges 1671, 3430, 9364.

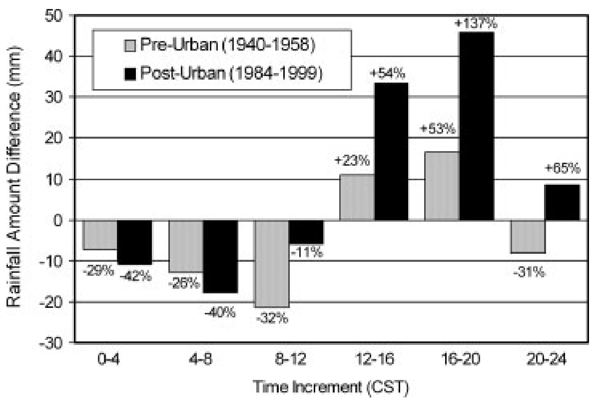

Figure 6. Magnitude and percentage differences between the average warm-season rainfall amount recorded in the UA versus the UCR for the pre- and post-urban time periods

warm-season rainfall than the UCR. The plot suggests that the magnitudes of the difference between the UA and UCR diurnal rainfall patterns are less in the pre-urban time period than in the post-urban time period. The difference between the UA and UCR for the midnight-to-noon time increments changes less significantly than the noon-to-midnight time increments from the pre- to post-urban time periods. Of particular note is the change in magnitudes of difference for the 12–16 and 16–20 time increments from the pre- to post-urban time periods. The much larger change in the 12–16 and 16–20 differences between the UA and UCR may be caused by a factor specific to that time increment present in the urban area in the warm seasons of the post-urban time period, suspected to be the UHI.

CONCLUSIONS

The objective of the research presented in this paper was to investigate the impact of urbanization on the diurnal rainfall pattern in Houston. An analysis of data from 19 raingauges in southeast Texas was performed to determine the differences in diurnal rainfall pattern between the rapidly urbanizing city of Houston and a UCR. In addition, the changes in diurnal pattern in both the urban-affected region and the UCR from a pre-urban time period (1940–58) to a post-urban time period (1984–99) were determined. Significant findings from the data analysis comparing the Houston UA with surrounding areas for the 1984–99 time period include:

- The average annual and warm-season diurnal rainfall distribution in the Houston urban area from 1984 to 1999 has an 18–28% higher fraction of the average daily rainfall occurring from noon to 4 p.m. compared with surrounding areas. This enhancement may be linked to the UHI (Shepherd and Burian, 2003).
- The Houston UA and hypothesized downwind UIR registered 59% and 30% respectively greater average warm-season rainfall amounts than a UCR from noon to midnight.
- The Houston UA had approximately 80% more rainfall occurrences between noon and midnight during the warm season than surrounding areas.

Significant findings from the comparison of diurnal rainfall distribution in the Houston urban area and surrounding areas for pre- (1940–1958) and post-urban (1984–1999) time periods include:

- The diurnal rainfall distribution has changed in southeast Texas from the 1940–58 time period to the 1984–99 time period. The changes are most significant in the Houston UA, especially for the afternoon time periods during the warm season.
- The average warm-season rainfall amount registered in the Houston UA increased by 25% from the pre-urban time period to the post-urban time period, while the average warm-season rainfall amount in the UCR decreased by 8%. The majority of the increase was observed for the noon to 4 p.m. and 4 p.m. to 8 p.m. time increments.

These results demonstrate the changes to the diurnal rainfall pattern in the Houston UA compared with surrounding areas and corroborate the results found for St Louis (Huff and Vogel, 1978) and Phoenix (Balling and Brazel, 1987). The possibility that UA influence the diurnal rainfall distribution and enhance afternoon rainfall amounts has important implications for urban water managers, flood control engineers, weather forecasters, emergency responders, and urban planners. The next step for this research is to determine whether the observed Houston rainfall anomalies are important from a hydrologic response perspective and, if so, how this information can be incorporated into drainage design and flood control.

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