

Detection of Urban-Induced Rainfall Anomalies in a Major Coastal City

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Popular Summary

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Urban heat islands (UHIs) are caused by the heat-retaining properties of surfaces usually found in urban cities like asphalt and concrete. The UHI can typically be observed on the evening TV weather map as warmer temperatures over the downtown of major cities and cooler temperatures in the suburbs and surrounding rural areas. The UHI has now become a widely acknowledged, observed, and researched phenomenon because of its broad environmental and societal implications. Interest in the UHI will intensify in the future as existing urban areas expand and rural areas urbanize. By the year 2025, more than 60% of the world's population will live in cities, with higher percentages expected in developed nations. The urban growth rate in the United States, for example, is estimated to be 12.5%, and the recent 2000 Census found that more than 80% of the population currently lives in urban areas. Furthermore, the U.S. population is not only growing but is tending to concentrate more in urban areas within the environmentally sensitive coastal zones. Urban growth creates unique and often contentious issues for policymakers related to land use zoning, transportation planning, agricultural production, housing and development, pollution, and natural resources protection. Urban expansion and its associated UHIs also have measurable impacts on weather and climate processes. The UHI has been documented to affect local and regional temperature, wind patterns, and air quality

This study, using "first of its kind" space-borne rainfall radar data, has identified Houston Rainfall Anomalies (HRAs) that are hypothesized to be caused by the UHI producing a wind circulation that interacts with local sea breeze and prevailing wind patterns. The results found higher rates over and downwind (North and East) of Houston in the annual and summer season months. Results are remarkably consistent with recent work identifying more lightning activity over and downwind of Houston but provides new data identifying rainfall anomalies. The study also presents evidence that the HRAs are linked to the urbanized region and not exclusively sea or bay breeze circulations

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Abstract

There is increasing evidence that large coastal cities, like Houston, Texas, can influence weather through complex urban land use-weather-climate feedbacks. Recent work in the literature establishes the existence of enhanced lightning activity over and downwind of Houston, Texas. Since lightning is a signature of convection in the atmosphere, it would seem reasonable that urbanized Houston would also impact the distribution of rainfall. This paper presents results using data from the world's first satellite-based precipitation radar (PR) aboard the Tropical Rainfall Measuring Mission (TRMM) and ground-based rain gauges to quantify rainfall anomalies that we hypothesize to be linked to extensive urbanization in the Houston area. It is one of the first rigorous efforts to quantify an urban-induced rainfall anomaly near a major U.S. coastal city and one of the first applications of space-borne radar data to the problem. Quantitative results reveal the presence of annual and warm season rainfall anomalies over and downwind of Houston. Several hypotheses have surfaced to explain how the sea breeze, coastline curvature, or urbanized Houston environment interacts with the atmospheric system to impact rainfall. This paper presents statistically significant evidence that the urban heat island's influence is of primary significance in causing the observed precipitation anomalies. Precipitation is a key link in the global water cycle and a proper understanding of its temporal and spatial character will have broad implications in ongoing climate diagnostics and prediction, Global Water and Energy Cycle (GWEC) analysis and modeling, weather forecasting, freshwater resource management, and land-atmosphere-ocean interface processes.

1. Introduction

Howard (1833a) made the first documented observation of a temperature difference between an urban area and its rural environment. Manley (1958) termed this contrast the “urban heat island (UHI)”. The UHI has now become a widely acknowledged, observed, and researched phenomenon because of its broad implications. It is estimated that by the year 2025, 60% of the world’s population will live in cities (UNFP, 1999). In the United States, the current urban growth rate is approximately 12.5%, with 80% currently living in urban areas. The U.S. population is not only growing but is tending to concentrate more in urban areas in coastal zones (Culliton et al. 1990). As cities continue to grow, urban sprawl creates unique problems related to land use, transportation, agriculture, housing, pollution, and development for policymakers. Urban expansion and its associated urban heat islands also have measurable impacts on weather and climate processes. The UHI has been documented in the literature to affect local and regional temperature distributions (Hafner and Kidder 1999), wind patterns (Hjemfelt, 1982), and air quality (Quattrochi, 1998). The UHI may also impact the global water cycle through development of clouds and precipitation in and around cities.

Several observational and climatological studies have theorized that the UHI can have a significant influence on mesoscale circulations and resulting convection. Early investigations (Changnon 1968; Landsberg 1970; Huff and Changnon 1972a) found evidence of warm seasonal rainfall increases of 9 to 17% over and downwind of major cities. The Metropolitan Meteorological Experiment (METROMEX) was an extensive study that took place in the 1970s in the United States (Changnon et al. 1977; Huff 1986) to further investigate modification of mesoscale and convective rainfall by major cities. In general, results from METROMEX have shown that urban effects lead to increased precipitation during the summer months. Increased precipitation was typically observed within and 50-75 km downwind of the city reflecting increases of 5%-25% over background values (Huff and Vogel 1978, Changnon 1979; Changnon et al. 1981; Changnon et al. 1991). More recent studies have continued to validate and extend the findings from pre-METROMEX and post-METROMEX investigations (Balling and Brazel 1987; Jauregui and Romales 1996; Bornstein and Lin 2000; Kusaka et al. 2000; Thielen et al. 2000; Baik et al. 2001; and Ohashi, and Kida 2002a). However, a recent U.S. Weather Research Panel report (Dabberdt et al. 2000) indicated that more observational and modeling work is required because previous results were heavily based on a few specific cities and statistical inferences.

Shepherd et al. (2002) recently established that space-based precipitation observing systems might be able to detect UHI-induced rainfall variability. This is particularly intriguing because understanding of urban effects on rainfall is far from complete. First, previous research used ground observations to study one or few selected cities. However, urban effects vary with the micro- to mesoscale features of individual cities. Globally assessment of urban climate is necessary to generalize the most important characteristics of urban effects. Second, previous studies, via different approaches, reached conflicting understanding on urban-rainfall relations. It is reported that urban reduces rainfall due to cloud microphysics (Ramanathan et al. 2001), although historical and more recent studies showed that urban enhances rainfall over and downwind of cities (see references in section 1). The mechanisms of urban effects on rainfall are complex. On one hand, cloud microphysics, in response to increased urban aerosols may reduce rainfall, as suggested by Rosenfield (1999). On the other hand, local dynamics and thermodynamics associated with an UHI-induced convergence zone and a destabilized boundary layer may enhance urban rainfall (Shepherd et al. 2002, Changnon and Westcott 2002, Ohashi and Kida 2002a).

There is increasing evidence that large coastal cities, like Tokyo, Japan and Houston, Texas, can influence weather through complex urban land use-weather-climate feedbacks. For a review of Tokyo's impact on urban rainfall can be found in Kusaka et al. (2000a) and Ohashi and Kida (2002a). An engineering study by Bouvette et al. (1982) presented statistical evidence from 4 Houston area rainfall-recording stations that the 24-hr 100-yr storm depth had increased by 15% in suburban areas when compared to the 24-hr 100-yr storm depth published in 1961 by the National Weather Service. They speculated that the change was linked to heavy urban development in Houston, which covers an area of 937 km². Orville et al. (2001) analyzed 12-years (1989-2000) of ground-based lightning data for the Houston area. They found that the highest annual and summer flash densities were over and downwind (e.g., Northeast-East) of the Houston area (Figure 1a). Using mesoscale model simulations (figure 1b), they hypothesized that the lightning distribution was caused by either a combination of urban heat island-induced convergence or enhanced lightning efficiency by increased urban aerosols. Since lightning is a signature of convection in the atmosphere, it would seem reasonable that urbanized Houston would also impact the distribution of rainfall. This paper presents results using data from the world's first satellite-based precipitation radar (PR) aboard the Tropical Rainfall Measuring Mission (TRMM) and ground-based rain gauges to quantify rainfall anomalies that we hypothesized to be linked to extensive urbanization in the Houston area. It is one of the first rigorous efforts to quantify an urban-induced rainfall anomaly near a major U.S. coastal city and one of the first applications of space-borne radar data to the problem.

2. Hypothesis and Houston Climatological Background

The primary hypothesis is that the central Houston Urban Zone and the seasonally-variant downwind regions (e.g. generally Northeast for Houston, but Northwest-Northeast during the summer) exhibit enhanced rainfall relative to regions upwind of the city. Section 3.0 will discuss the methodology for defining the upwind control regions and the downwind "urban impacted regions." Possible mechanisms for the urban-induced rainfall 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 are further examined in future work. Here, the primary objective is to utilize a unique satellite-based rainfall data set to support the guiding hypothesis and provide quantification of this phenomenon. Furthermore, we seek to corroborate very recent findings related to the Houston lightning anomaly (Orville et al. 2001).

Houston sits on the 5,000 km² Gulf Coastal Plain with an elevation of 27 m above sea level. The entire eastern third of the state of Texas including the Houston area (upwind and downwind) is considered a sub-tropical humid climate. Southeast Texas receives, on average, more than 140 cm of rain annually (Lyons 1990). Since Houston is located near Galveston Bay and the Gulf of Mexico, Houston weather is significantly influenced by sea breeze circulations, particularly during the warm season months. An analysis of annual surface wind direction by the National Weather Service spanning the years 1984-1992 indicates that the prevailing surface flow is from the southeast. This would indicate the dominance of the sea breeze circulation. As indicated later in section 3.0, the steering level flow (e.g. 700 hPa) and mid-level flow are typically more southwesterly. This fact has important implications for how the upwind and downwind regions are defined in this study. Sea-bay breeze circulations (Pielke and Segal, 1986) and coastline irregularities

(McPherson 1970) are well-known forcing agents for convection, however, we present results that support the hypothesis that the urbanization in the Houston area is a primary factor causing the observed anomalies. Figure 2 is an image from the Geostationary Operational Environmental Satellite (GOES) that shows the extent of Houston's UHI. The 3.9 micron infrared channel on GOES is used to depict relatively cold and warm surfaces. Cooler regions like rivers or lakes are indicated as whiter shades while warmer areas are indicated by darker shades. The thermal perturbation of the Houston UHI is clearly evident. The magnitude (e.g. mean urban temperature – mean rural temperature) of the Houston UHI, like previously studied cities, is typically proportional to the city size (Oke 1981) and most apparent after sunset (Oke 1987). However, the UHI circulation is more clearly observed during the daytime than nighttime because of the urban-rural pressure gradient and vertical mixing during daytime hours. As hypothesized in the following text, these dynamic factors will play a major role in the observed rainfall anomalies (Shreffler 1978; Fujibe and Asai 1980).

3. Methodology

TRMM was launched in November 1997 as a joint U.S.-Japanese mission to advance understanding of the global energy and water cycle by providing distributions of rainfall and latent heating over the global tropics. The TRMM PR operates at a frequency of 13.8 GHz and can achieve quantitative rainfall estimation over land as well as ocean. The horizontal resolution of 4.3 km at nadir and about 5 km at the scan edge allow the TRMM PR to observe small convective cells as well as larger systems. TRMM is in a precessing, low-inclination (35°), low-altitude orbit, and because of the non sun-synchronous orbit strategy, the equatorial crossing time gradually shifts. For this reason, it is unlikely that results reflect any biases from diurnal forcing.

The study employs the “control coordinate system” approach of Shepherd et al. (2002). The study identified the most frequent lower tropospheric wind flow for Houston, annually and by season, and defined the hypothesized “downwind urban impacted region” and upwind control regions. Figure 3 is an example of the theoretical coordinate system. The black vector indicates that the mean annual 700-hPa wind direction over the Houston area is from 230° (~southwesterly). It serves as the horizontal reference axis (HRA) that determines the orientation of the control coordinate system. 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 (Hagemeyer 1991). Wind direction data covering the years 1979-1998 from the NCEP/NCAR 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 HRA is oriented according to the mean prevailing wind direction. The 125° sector in the downwind urban impacted region (DUIR) accounts for the mean direction and the spread of values that encompass the mean direction (e.g. the deviation).

Space-time averaged PR data are utilized to investigate rainfall modification due to urban effects. The analysis was conducted on mean monthly rainfall rates (mm/h) at a height of 2.0 km. Rainfall rates were calculated as a part of the standard reflectivity-rainfall rate algorithm described in NASDA and NASA (2000). The PR algorithm calculates rain statistics only when rain is judged to be certain in a 0.5° cell (as opposed to clutter, noise, etc.). Following the sampling analysis procedure of Bell and Reid (1993), each 0.5° grid box contains well over 1000-2000 samples for the 52-month period of this study. For more detailed analysis, the mean rainfall rate value at each grid cell was calculated over the period (January 1998-May 2002, excluding August 2001). For a given grid box, a total of 52 mean monthly rainfall rates were averaged. For the seasonal analysis, only the months corresponding to the season are included. In terms of accuracy,

Kummerow et al. (2000) reported that comparisons of PR-measured radar reflectivities with those measured by ground-based radar at NASA's Florida ground validation site show good agreements (differences within about 1 dB).

4. Results

Analysis of the mean annual rainfall rates for Houston and surrounding areas supports the research hypothesis and is consistent with lightning results reported by Orville et al. (2001). In figure 3, the orange oval (Urban Zone-UZ) covers 0.5° grid boxes centered on $(29.75^\circ, 95.75^\circ)$ and $(29.75^\circ, 95.25^\circ)$, respectively. The black vector represents the mean annual 700-hPa steering wind direction used to define the upwind control region (UCR-rectangular box) and the downwind urban impacted region (DUIR-pentagon). The DUIR has a pentagon shape because of the attempt to create an approximately 125° sector in the downwind region to account for variability in the mean steering direction. The sides that are parallel to the wind vector are ~ 150 km in length. The orthogonal side is ~ 300 km in length. In the UCR, the rectangular box is roughly $150 \text{ km} \times 300 \text{ km}$. This approach was utilized successfully in Shepherd et al. (2002) and is based on an earlier approach in St. Louis by Huff and Changnon (1972a).

The largest rainfall rates are located in the eastern UZ (orange oval) and DUIR, particularly Northeast of the city. As table 1 indicates, the mean rainfall rate in the DUIR is 2.97 mm/h. The maximum rate in the DUIR is greater than 3.7 mm/h. In the urban zone, the mean rainfall rate (albeit only 2 grid boxes) is 2.66 mm/h. In the UCR, the mean rainfall rate is 2.06 mm/h. Table 1 indicates that the mean rainfall rate in the DUIR (UZ) is 44% (29%) larger than UCR. Referring back to figure 1, Orville et al. (2001) also found evidence of elevated lightning flash rates in the locations of the rainfall anomalies. It is clearly evident that the northwestern to southeastern sectors of the study area do not contain as many occurrences of higher rainfall rates compared to the climatologically-indicated downwind regions to Northeast to East of the city.

4.1 Seasonal Stratification

The overwhelming consensus from the METROMEX studies of St. Louis is that urban effects on precipitation are most pronounced during the warm-season months (Huff and Changnon 1972a; Changnon et al. 1991, Jauregui and Romales 1996). Therefore, the results in this study were further stratified by season. The seasons were designated as summer (June-August), fall (Sept.-Nov.), winter (Dec.-Feb.), and Spring (March-May).

Season (Mean 700-hPa direction)	Mean Rainfall Rate in UCR (mm/h)	Mean Rainfall Rate in DUIR (mm/h)	Mean Rainfall Rate in UZ (mm/h)	% Change (UCR to DUIR)	% Change (UCR to UZ)
Annual (230°)	2.06	2.97	2.66	44%	29%
Summer (178°)	2.97	3.79	4.66	28%	57%
Fall (210°)	2.32	3.09	1.73	33%	-25%
Winter (266°)	1.42	2.02	1.69	42%	19%
Spring (267°)	2.81	3.95	3.23	40%	15%

Table 1-Mean rainfall rates and relative rainfall rate variance in the upwind control region (UCR), downwind urban impacted region (DUIR), and urban zone (UZ).

Figure 4 shows the results of the seasonal stratification. The most dramatic shift in coordinate system orientation is observed in the summer season when the prevailing flow at the steering levels shifts from southwesterly in June to southeasterly in August, resulting in a mean summer vector of 178° . Analysis of the results reveals consistencies with the historical work of the 1970s and more recent work by Orville et al. (2001). The largest mean rainfall rates during the summer season are found over the urban zone and in the DUIR, north to northeast of the urban area. Table 1 indicates that the mean rainfall rate in the summer DUIR (UZ) is 3.79 mm/h (4.66 mm/h). The mean rainfall rate in the summer UCR is 2.97. There is a 27.6% (56.9%) increase in the mean rainfall rate in the DUIR (UZ) over the UCR. It is particularly interesting to note the large increase in the summer UZ relative to the UCR. This fact provides strong evidence that the urban forcing is further enhanced during the summer months.

To further corroborate, the summer rainfall anomaly over the city, an analysis of annual and warm season totals from 13 years (1984-1997) of high-density rain gauges was conducted. Rain gage data was obtained from the National Climatic Data Center (NCDC) and the City of Houston Office of Emergency Management (OEM). Rainfall records from the NCDC were extracted from CD-ROMs distributed by Hydrosphere, Inc. and the Houston OEM data were downloaded from their web site. The rainfall records were screened to remove ones outside the area of study and ones with insufficient data coverage or quality. After initial screening, 230 NCDC daily, 86 NCDC hourly, and 32 NCDC 15-minute gages, and 121 Houston OEM 15-minute gages remained for use in the study. The analysis in figure 5 reveals elevated rainfall amounts during the warm season over the city in the fourteen-year record. In the five year TRMM satellite-based record, it is also evident that a rainfall anomaly is apparent over the city in comparison to the annual distribution. It is encouraging to find a consistent signature in the coarser satellite dataset and the higher resolution rain gage dataset.

It is particularly interesting to note how the general magnitude of the rainfall rates increase (relative to the Fall and Winter) over the UZ and DUIR in the summer months. This is indicative of the more convective nature of the precipitation during this time period. The most likely reason for pronounced urban effects on rainfall during the warm season is smaller large-scale forcing (e.g. frontal systems or baroclinicity). Advection associated with strong large-scale forcing tends to eliminate thermal differentiation between urban and surrounding areas. Also, during the warm season, the UHI-induced mesoscale convergence and circulation is more dominant and can significantly alter the boundary layer and interact with the sea-breeze circulation. Examining figure 4, it is less evident during the spring, fall, and winter that a dominant urban area and downwind anomaly exists. One could argue that there is slight enhancement in the winter DUIR. Changnon et al. (1991) found some evidence that St. Louis could alter winter, fall, and spring precipitation. The figure also indicates a more diffuse rainfall pattern during the fall and spring seasons. The climatological likelihood of large-scale precipitation forcing during these transitional seasons explains such patterns and the lack of an urban-sea breeze mesoscale signature.

4.2 Texas Coastal Analysis

As stated earlier, Houston lies within a coastal zone and is greatly impacted by the sea-Galveston Bay breeze circulation and a complex coastline. McPherson (1970), Negri et al. (1994) and Baker et al. (2001) showed that convex coastline curvature could enhance convective development by creating convergence zones for sea-breeze circulations. It might be suggested that the sea/bay-breeze-coastline interactions should explain the Houston lightning and precipitation anomalies presented in this study. To investigate this possibility, the entire Texas coast was divided into 7 zones that extend

100-km inland. The rationale is that there are at least 4-5 major inlets or bays along the Texas coast. The working hypothesis is that if sea-breeze coastline curvature is considered a primary convective forcing mechanism for the observed anomalies, then enhanced regions should be found in several locations along the coast. Conversely, if the urban heat island and its interaction with mesoscale circulations were of primary significance, then an anomaly in precipitation would be expected in the urbanized regions near Houston. In figure 6, a plot of the TRMM-derived mean annual rainfall rates for 52 months are plotted for the coastal zones. It is very evident that an anomaly in precipitation rate (mean rates > 3.0 mm/h) is located in coastal zones 6 and 7. These zones (in and downwind of Houston) represent coastal regions where the sea breeze-bay breeze circulations can interact with the urban circulation. Yoshikado (1994), Kusaka et al. (2001), and Ohashi and Kida (2002a) published modeling studies illustrating the potential convective forcing that can result from sea breeze and UHI interactions. They all present strong evidence that vertical motion and convergence fields are significantly stronger over the urban land surface and can impact convective processes. Coastal zones 1-5 (some of which include complex coastline curvature but no major urban-industrial area) do not exhibit statistically significant differences in rainfall rate. A similar plot for the summer months is extremely consistent with this finding and results are plotted in the zone-rainfall rate bar graph of figure 6.

4.2 Urban Rainfall Ratio Analysis

The evidence presented in previous sections provides new insight and evidence that urban influences are likely tied to the observed Houston Rainfall Anomalies. Furthermore, the consistency of the anomaly shift as a function of the changing prevailing flow is also strong evidence in support of our hypothesis. One additional piece of evidence is the calculation of the Urban Rainfall Ratio (URR). This parameter was first introduced in Shepherd et al. (2002). The URR is,

$$URR = R_i/R_{BG}. \quad (1)$$

R_i is the mean rainfall rate at a grid box over the 52-month study period. R_{BG} is the mean background rainrate over the UCR-DUIR-Urban Zone domain. Essentially, the URR is a measure of the relative magnitude of a given point to a background value. Values greater (less) than one are positive (negative) anomalies. An analysis of the percentage of URR's in the UCR, DUIR, and Urban Zone, respectively, greater than 1.0 is instructive (figure 7). The most striking result is that for the annual (warm season) cases, 82% (100%) of the URR's in the upwind region are less than 1.0. This finding indicates that values in that region are generally smaller than the mean background value of the entire coordinate system. Conversely, 88% (72%) of annual (warm season) URR's in the downwind urban impacted region are greater than 1.0, which indicates that rainfall rates in the downwind region are likely to be larger than the background value. The results also illustrate that 50% (100%) of the annual (warm season) URR's in the urban zone are greater than 1.0, which supports the hypothesized warm season anomaly over the urban zone. In the warm season, the majority of the urban zone and downwind region gridpoints are at least 20% (e.g. > 1.2) larger than the background value.

5.0 Conclusions, Future Work, and Implications

This statistical and quantitative analysis of "first of its kind" space-borne rainfall radar data has identified Houston Rainfall Anomalies (HRA) that are hypothesized to be caused by an urban land use interactions with atmospheric processes. The results found elevated rates over and downwind of Houston in the annual and warm season datasets, as hypothesized. Results are remarkably similar to the lightning anomalies of Orville et al.

(2001), and they confirm speculative assertions introduced by Bouvette et al. (1982). The study also presents evidence that the HRAs are linked to the urbanized region and not exclusively sea or bay breeze circulations. It is likely that an interaction between a UHI convergence/circulation pattern and the sea-breeze circulation explain the anomalies. At this time, the role of microphysical (e.g. aerosol) forcing is unclear and more research is required.

Future work will integrate the TRMM PR analysis with an extensive high-density rain gauge analysis using a “downscaling” process. Additionally, numerical modeling of the Houston UHI-sea breeze-Galveston bay breeze will be conducted to assess what forcing mechanisms (roughness, destabilized boundary layer, mesoscale interactions, or microphysics) may result in the HRAs. A climate change study will leverage a high-density, long-term rain gauge dataset against land use and population density data to detect the temporal evolution of the HRA relative to urban-industrial development around Houston. Finally, an engineering study will be conducted to update rainfall frequency analyses used in urban drainage design, transportation design, agriculture, and other practical applications. Additionally, the Houston Environment Aerosol Thunderstorm (HEAT) experiment (Orville et al. 2002) will provide a unique dataset in the 2004-2005 timeframe to further investigate these findings.

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a.



b.

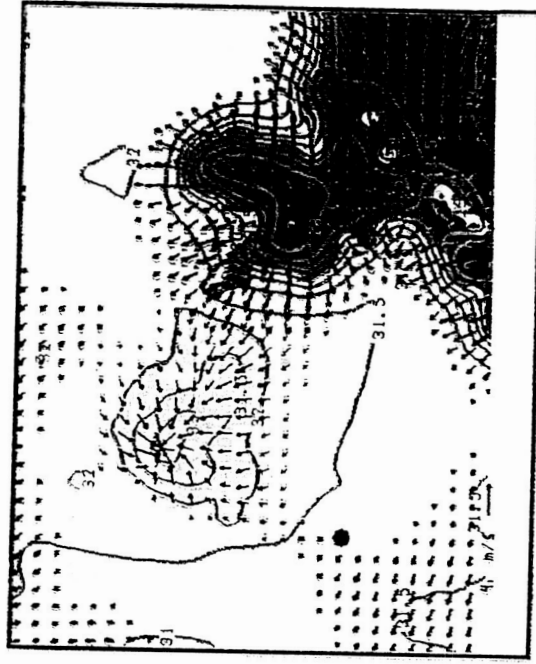


Figure 1. a. Mean Annual Flash Densities (per square kilometer per day): Highest Flash Densities (> 4 square kilometers) are over and just downwind of the Houston Urban area **b.** MM5 Simulation of low-level convergence field illustrating the interaction between the sea breeze circulation and the urban heat island circulation (following Orville et al. 2001)

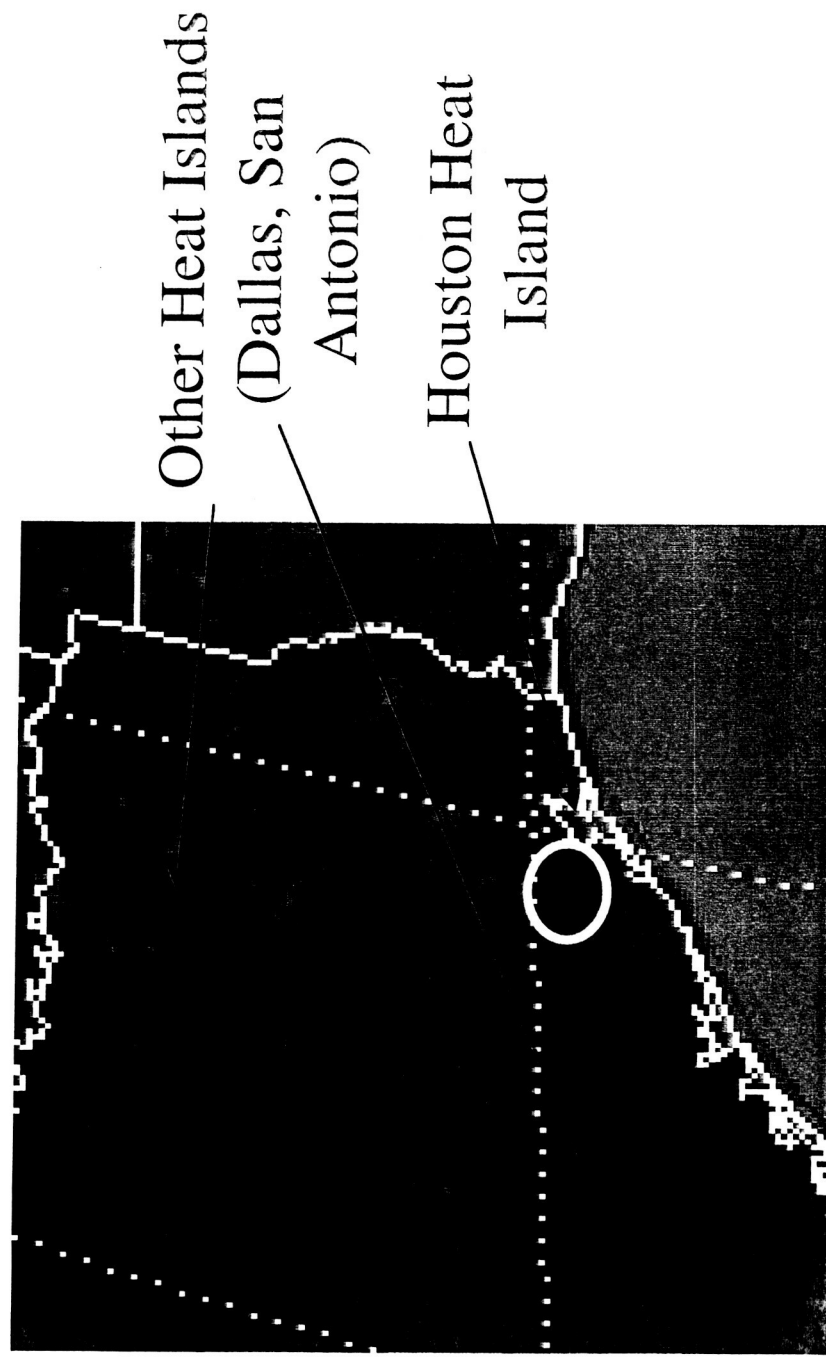
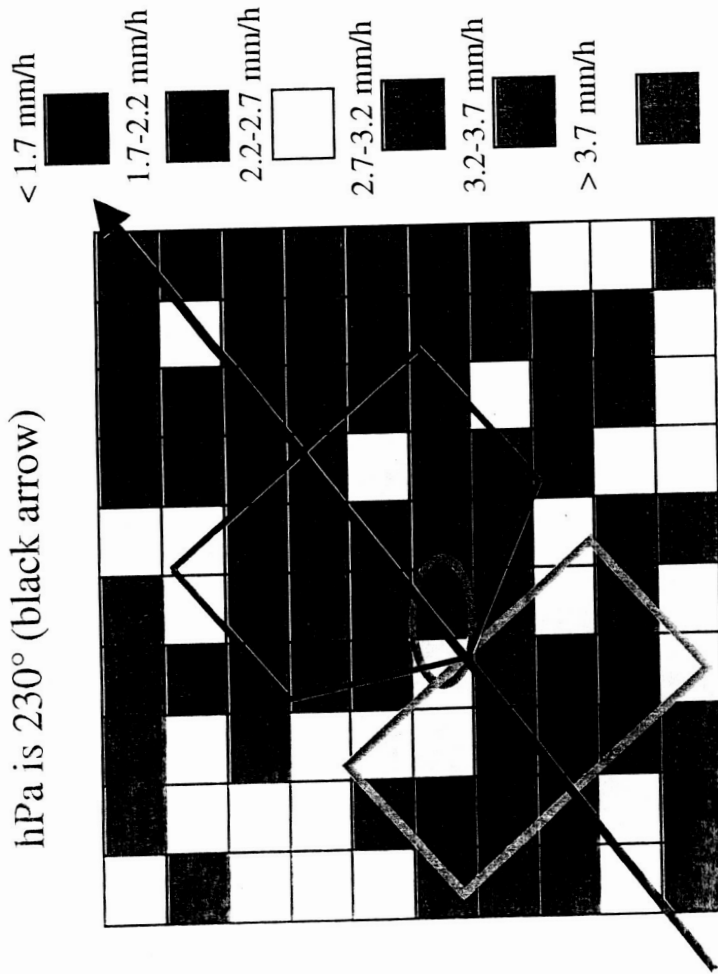


Figure 2-Geostationary Operational Environmental Satellite (GOES) 3.9 micron channel indicated thermal signatures of the Houston urban heat island.

Mean Reference Wind Direction at 700
hPa is 230° (black arrow)



0 100 200 Kilometers

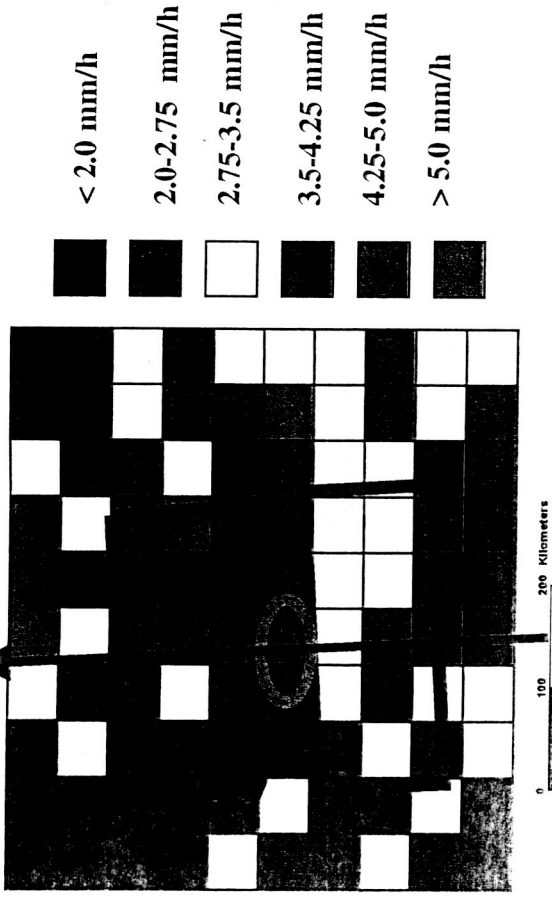
TRMM PR at 0.5 Degree with
Coordinate System

Houston Area with Coordinate
System and Gauge Locations

Figure 3-The “theoretical study coordinate system” with mean annual distribution of TRMM-derived rainfall rates from January 1998 to May 2002 (excluding August 2001). The orange oval is the approximate Houston Urban Zone and is centered on (29.75, 95.75) and (29.75, 95.25), respectively. The black vector represents the mean annual 700 hPa steering direction. The pentagon-shaped box is the “downwind urban impacted region (DUIR)” and the rectangular box is the “upwind control region (UCR)”.

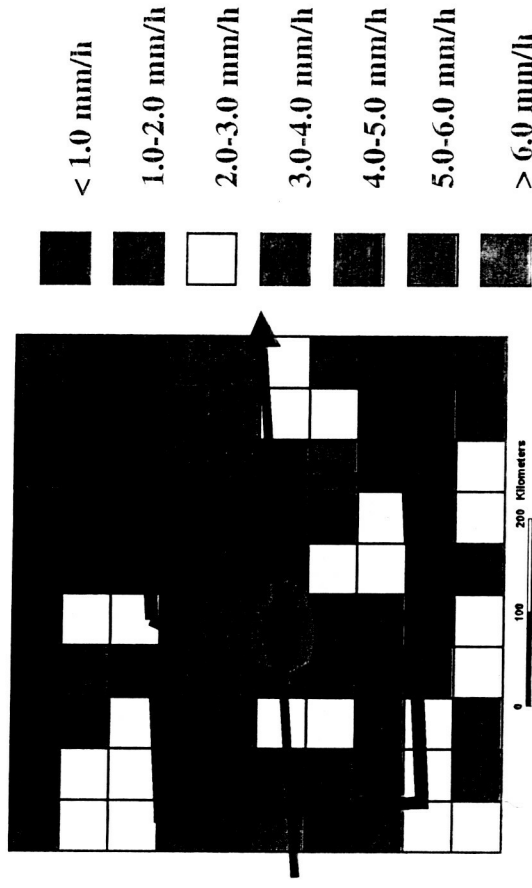
Summer Coordinate System

700 hPa Mean Annual Direction 178°



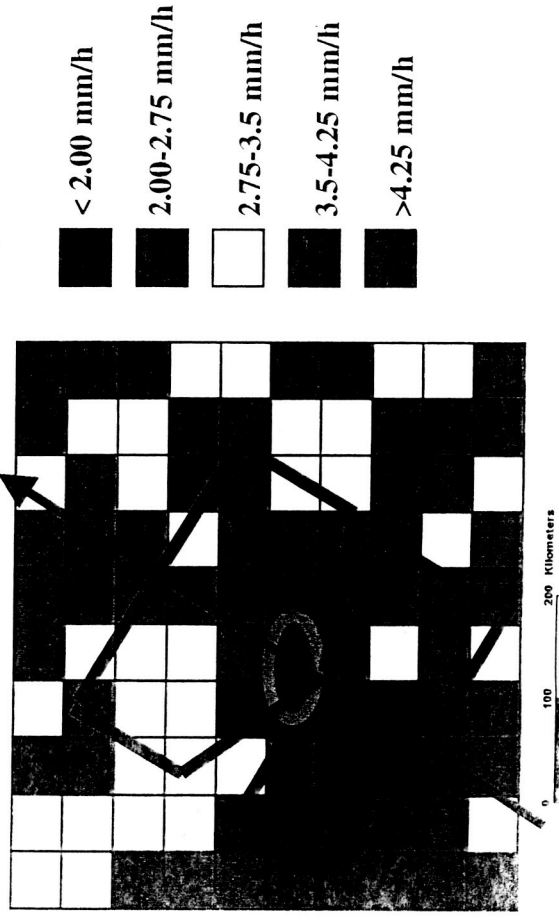
Spring Coordinate System

700 hPa Mean Annual Direction 267°



Fall Coordinate System

700 hPa Mean Annual Direction 210°



Winter Coordinate System

700 hPa Mean Annual Direction 266°

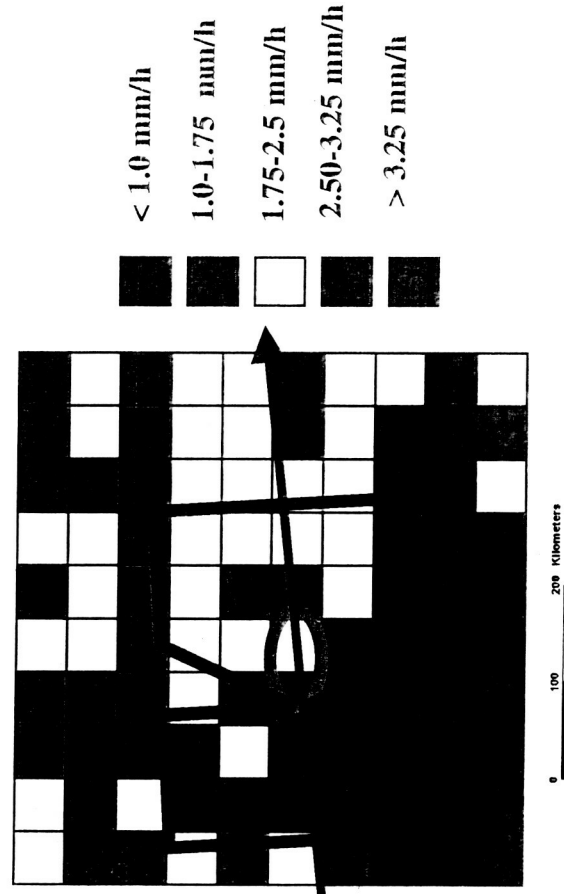


Figure 4-Seasonal stratification of mean TRMM-derived rainfall rates over the 52 month study period (mm/h).

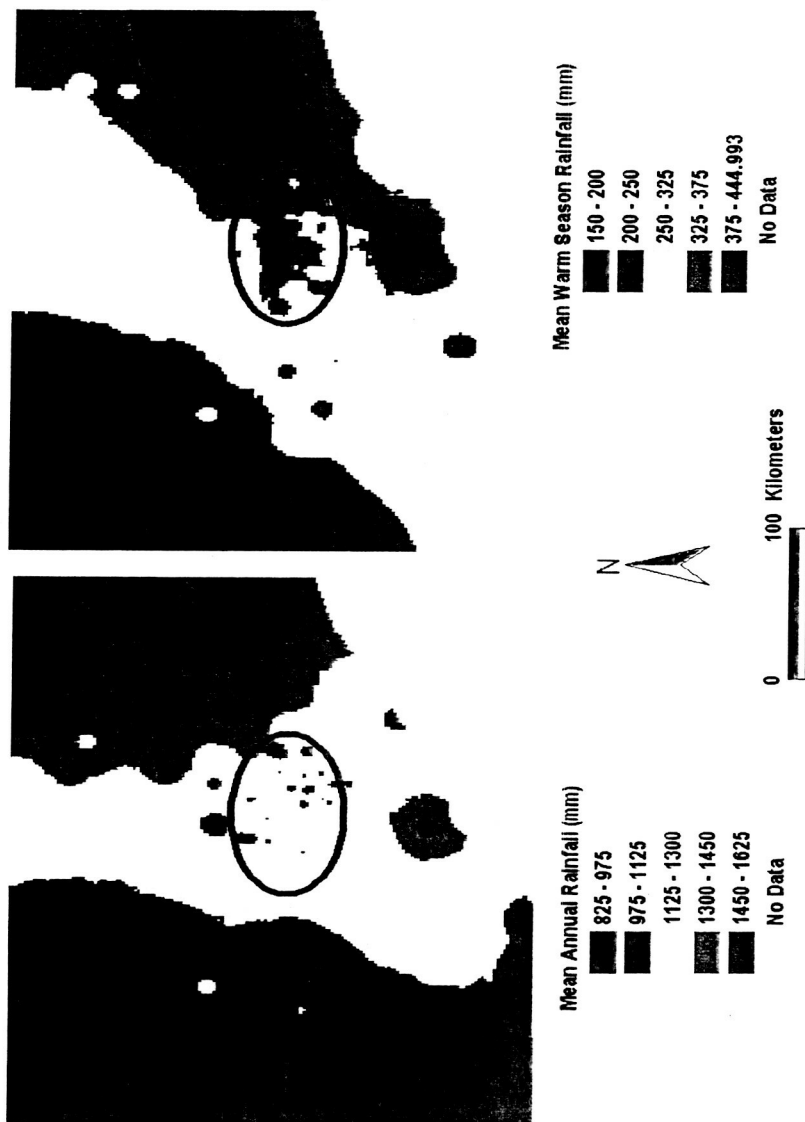


Figure 5-Analysis of rain gauge totals from quality-controlled gauges in a dense urban network (e.g. within 250-km of Houston: 121 Houston Flood Alert, 230 NCDC daily, 86 NCDC hourly, and 32 NCDC 15-minute). A greater urban influence is seen in the warm season spatial rainfall distribution compared to the annual rainfall distribution over the 13 year period.

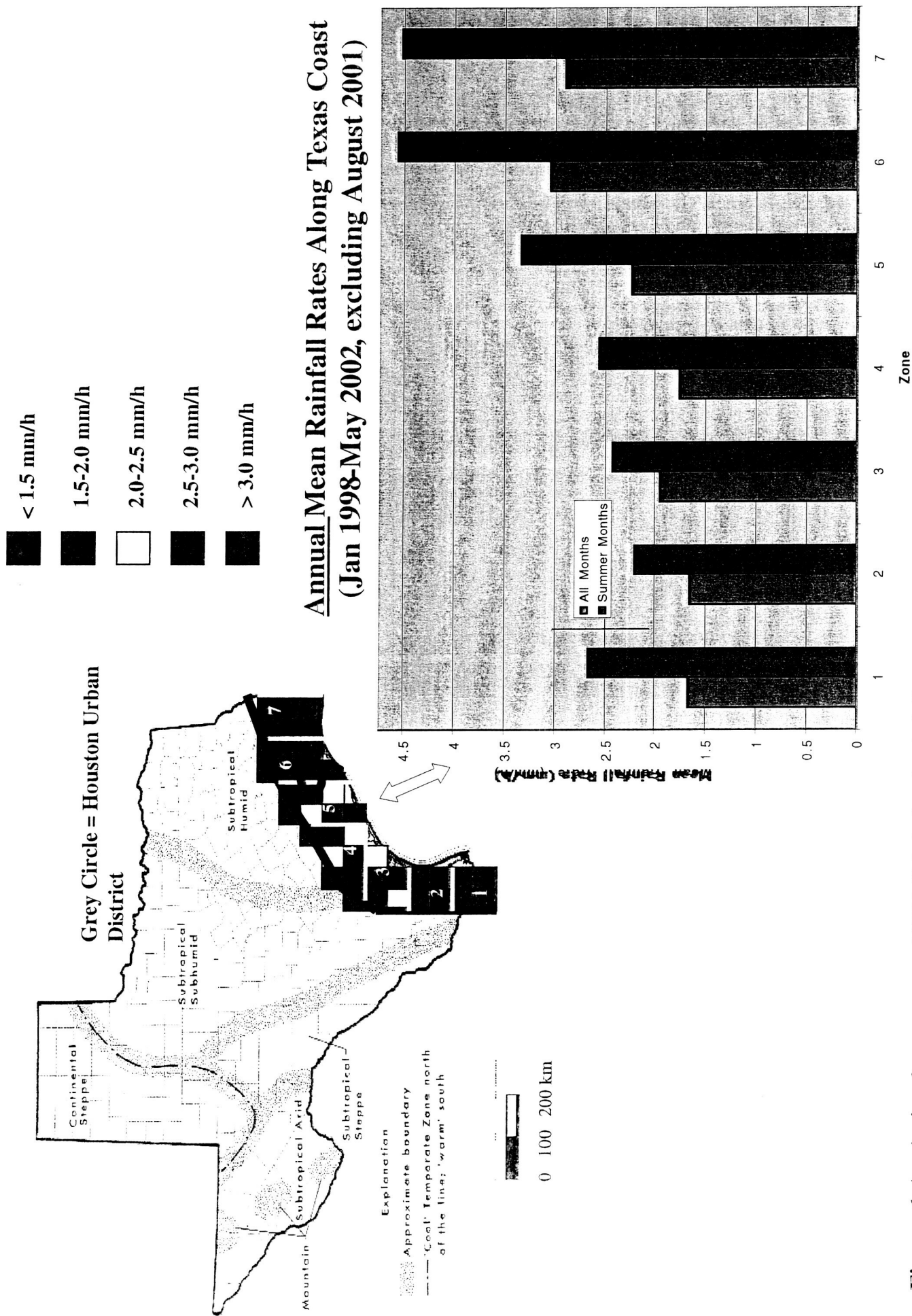


Figure 6-Analysis of mean annual TRMM-derived rainfall rates in the seven Texas Coastal zones (mm/h).

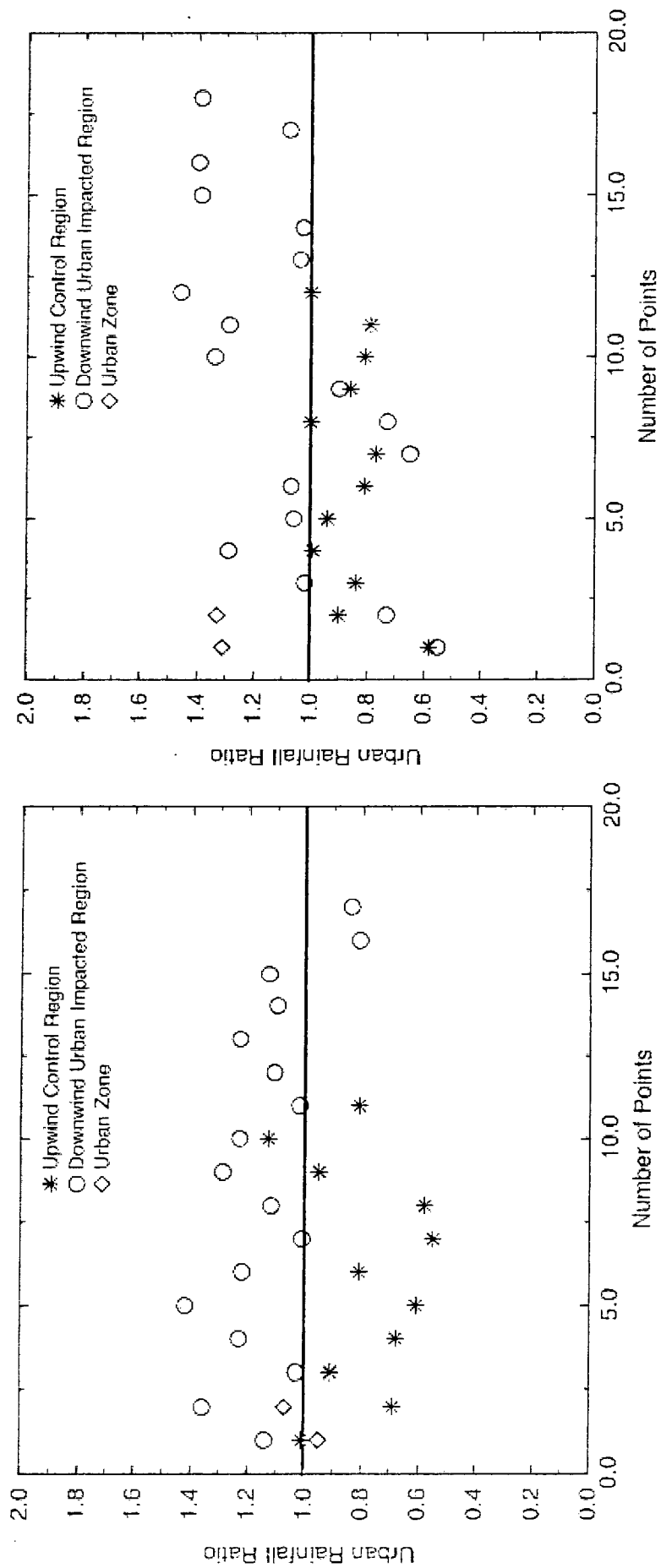


Figure 7-Plot of Urban Rainfall Ratio for the annual (left) and summer (right) datasets.