P2.11 A DOWNSCALING ANALYSIS OF THE URBAN INFLUENCE ON RAINFALL: TRMM SATELLITE COMPONENT

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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 (Bornstein and Lin, 1999). 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 the1970s 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; Thielen et al. 2000; Baik et al. 2001; and Shepherd et al. 2002). 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.

There is increasing evidence that large coastal cities, like Houston, Texas, can influence weather through complex urban land use-weather-climate feedbacks. A hydrologic-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 what is now the fourth largest U.S. city, covering an area of 937 km^2. 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. 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. Herein, we present an overview of the hypotheses, methodology, results and discussion, a synopsis of future research on the problem, and key science, engineering, and socio-economic implications of the research.

2. HOUSTON CLIMATE AND hYPOTHESES

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.

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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 km^2 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.

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 2 is an example of the mean annual distribution of rainfall rates from January 1998 to May 2002 (excluding August 2001, at which time the satellite underwent orbit adjustments). 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 in 0.5° x 0.5° grid cells. 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 of rain occurrence 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 2, the orange oval (Urban Zone-UZ) covers 0.5° grid boxes centered on (29.75°, 95.75°) and (29.75°, 95.25°), 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 km × 300 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 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. Statistical t-tests indicate that differences are significant at 95% confidence levels (or greater) for results presented herein.

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). Figure 3 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 (urban zone) 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. An analysis of annual and warm season totals from 13 years (1984-1997) of high-density rain gauges indicates elevated rainfall amounts North and East of Houston as the satellite rainfall rates suggest (Figure 4). The authors will report on a unique downscaling analysis integrating satellite and rain gauge data in a future body of work.

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 dominate and can significantly alter the boundary layer and interact with the sea-breeze circulation. Examining figure 3, 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. Figure 5 represents a stratification of the mean annual rainfall rates by rainfall rate intensity. The most striking result from the analysis is that at the very lowest rainfall rates (< 2.0 mm/h) the majority of occurrences are outside of the DUIR. At increasingly larger rainfall rate strata, the frequency of occurrence is greater in the DUIR. This data is further confirmation of a convective signature in the downwind urban-impacted region.

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) published a modeling studying illustrating the potential convective forcing that can result from sea breeze and UHI interactions. He showed maximum vertical motion occurred in his model simulation in the convergence zone of the sea breeze and the urban heat island circulation growing over the inland side of Tokyo, Japan around 1200 LT. Coastal zones 1-5 (some of which include complex coastline curvature but no major urban-industrial area) do not exhibit such 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.

4.3 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). URR is simply,

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

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, that are greater than 1.1 or 10% larger than the background value is instructive. The most striking result is that for the annual (summer) cases, 70.5% (38.8%) of the URR values are greater than 1.1 in the DUIR. On the other hand, in both strata, 0% of the values in the UCR are greater 1.1. For the annual case, 71% of the urban zone URR values are greater than 1.1. These results indicate a greater likelihood of positive anomalies in the DUIR or Urban Zone and negative anomalies in the UCR.

5.0 CONCLUSIONS, FUTURE WORK, 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.

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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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).

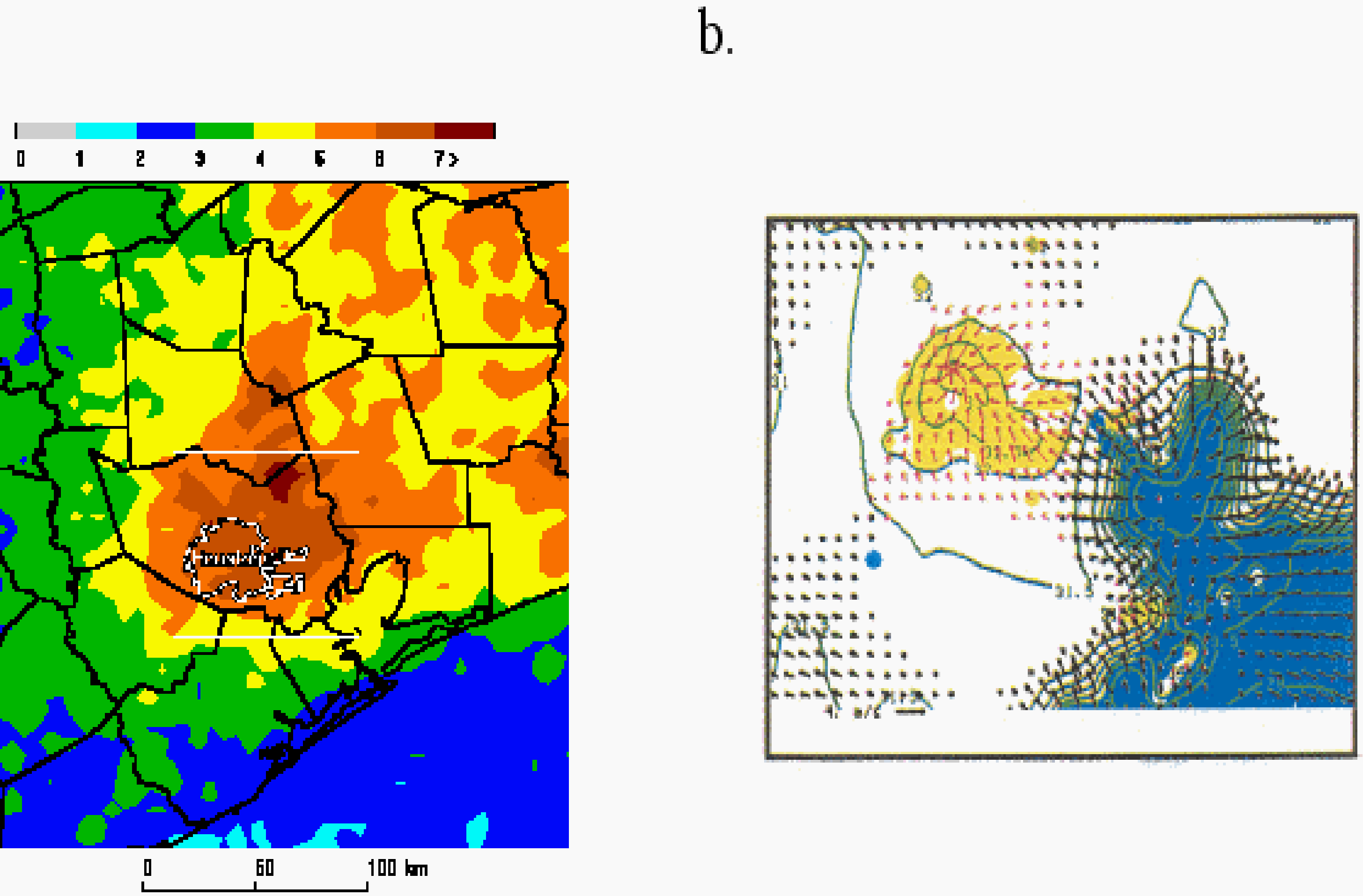

Figure 1.-**a.** Mean Annual Flash Densities (km^{-2} day^{-1}): Highest Flash Densities are over and just downwind of the Houston area. **b.** MM5 simulation of low-level convergence illustrating the interaction between the sea breeze and urban heat island circulations (following Orville et al. 2001).

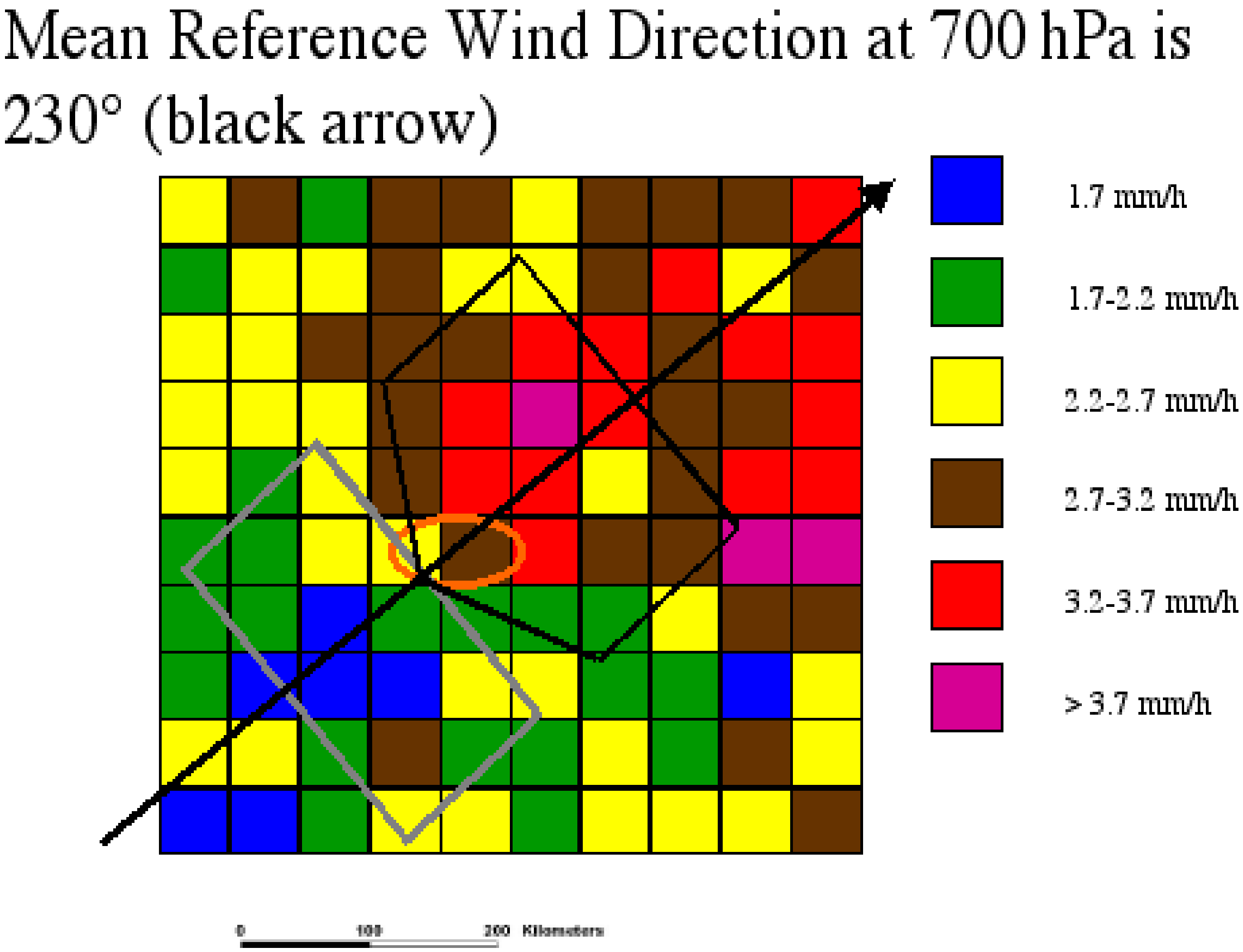

Figure 2-The “theoretical study coordinate system” with mean annual distribution of TRMM-derived rainfall rates from January 1998 to May 2002 (excluding August 2001). The orange oval is the approximate Houston Urban Zone (UZ) and is centered on (29.75°, 95.75°) and (29.75°, 95.25°). The black vector is the mean annual 700 hPa steering direction. The pentagon-shaped box is the “downwind urban impacted region” or DUIR. The rectangular box is the “upwind control region or UCR”.

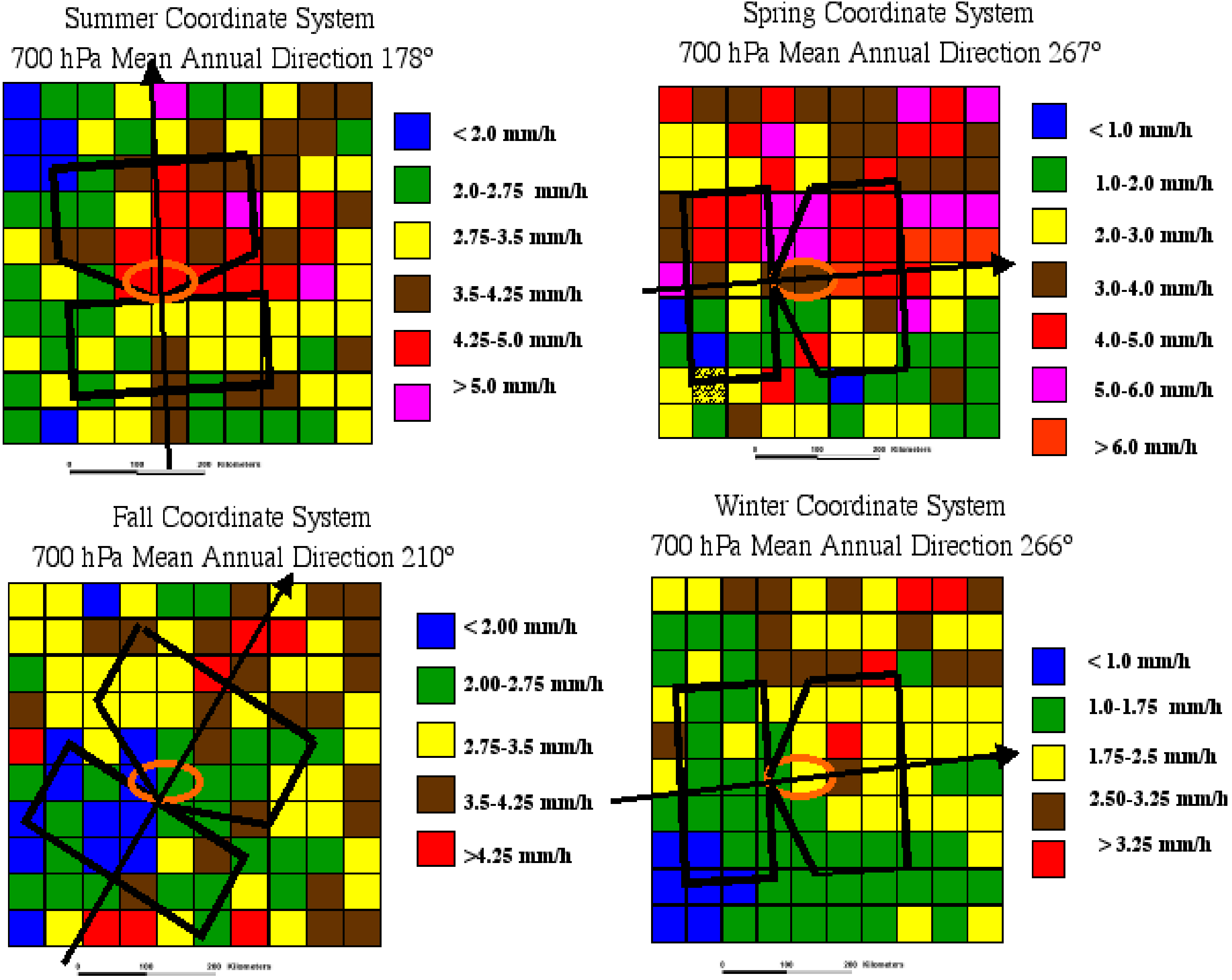

Figure 3-Seasonal stratification of mean TRMM-derived rainfall rates (mm/h) over the 52 month period.

Spatial Distribution Rainfall
Based on Rain Gauge Data

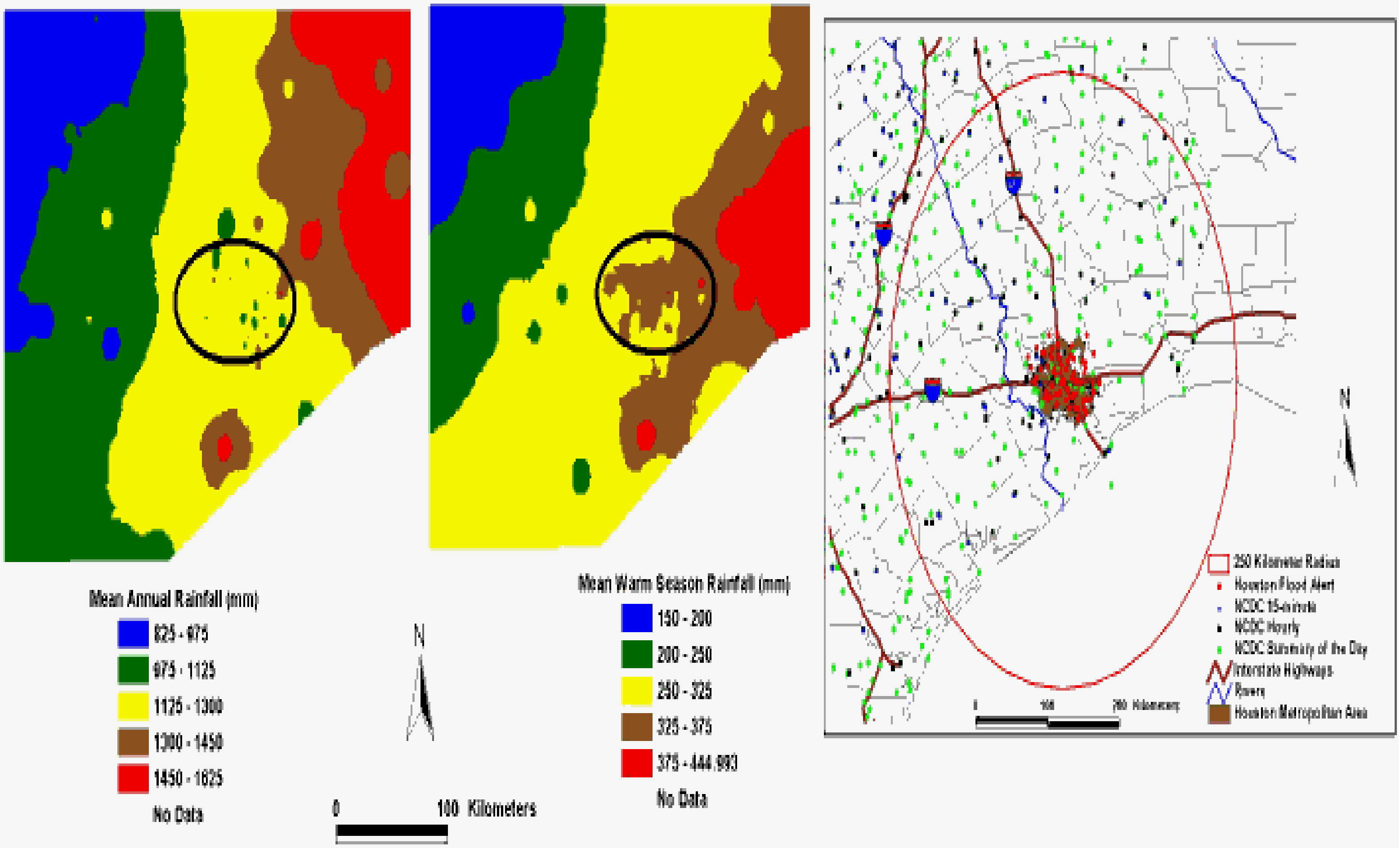

Figure 4-Analysis of rain gauge totals from quality controlled gauges in a dense Houston network (e.g. within 250 km of Houston: 121 Flood Alert guages, 230 NCDC daily gauges, 86 NCDC hourly gauges, and 32 NCDC 15 minute gauges. A greater urban influence over the city is seen in the warm season distribution compared to the annual rainfall distribution (consistent with TRMM distribution in figure 3).

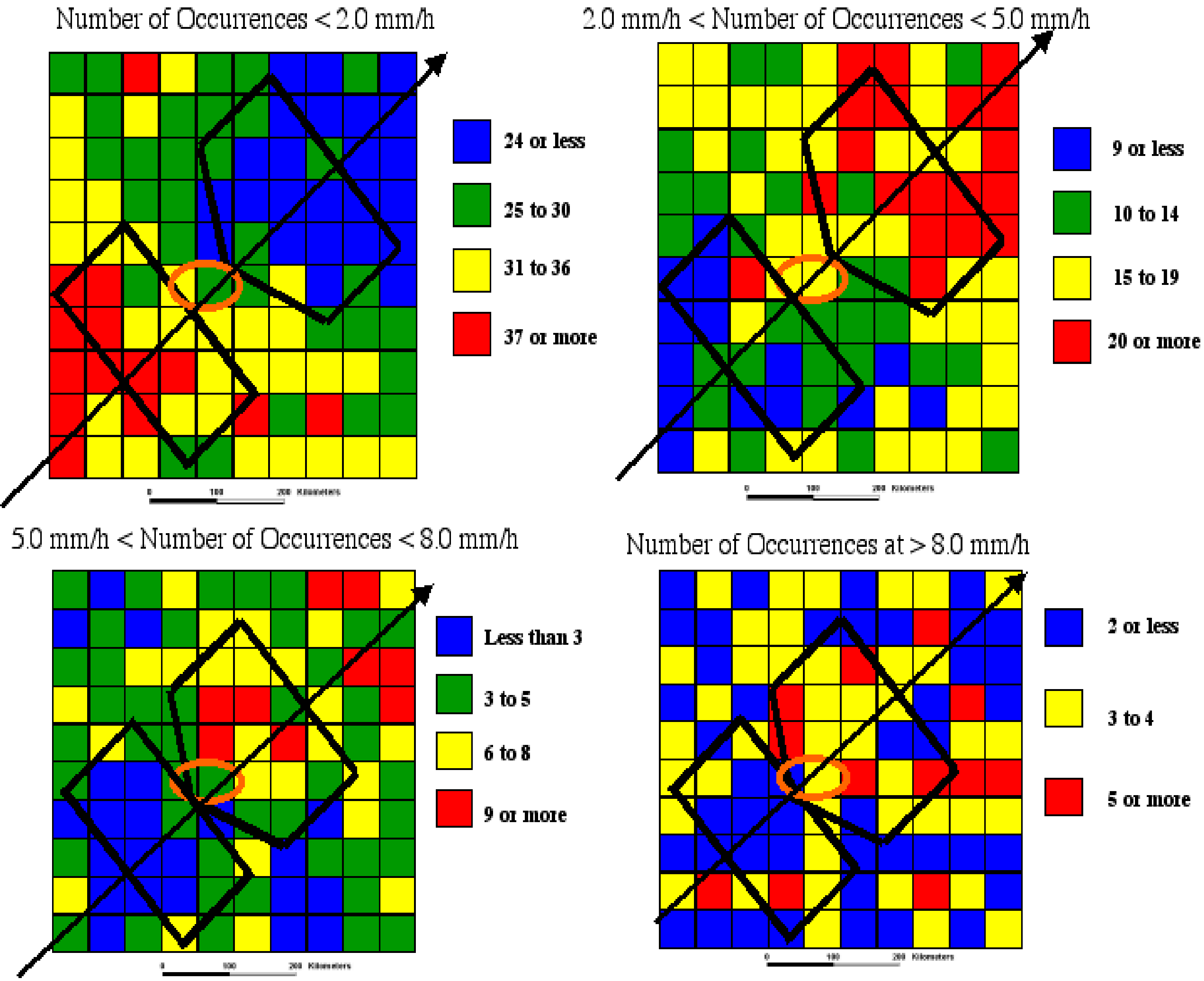

Figure 5-Rainfall rate intensity stratification of mean annual TRMM-derived rainfall rates (mm/h).

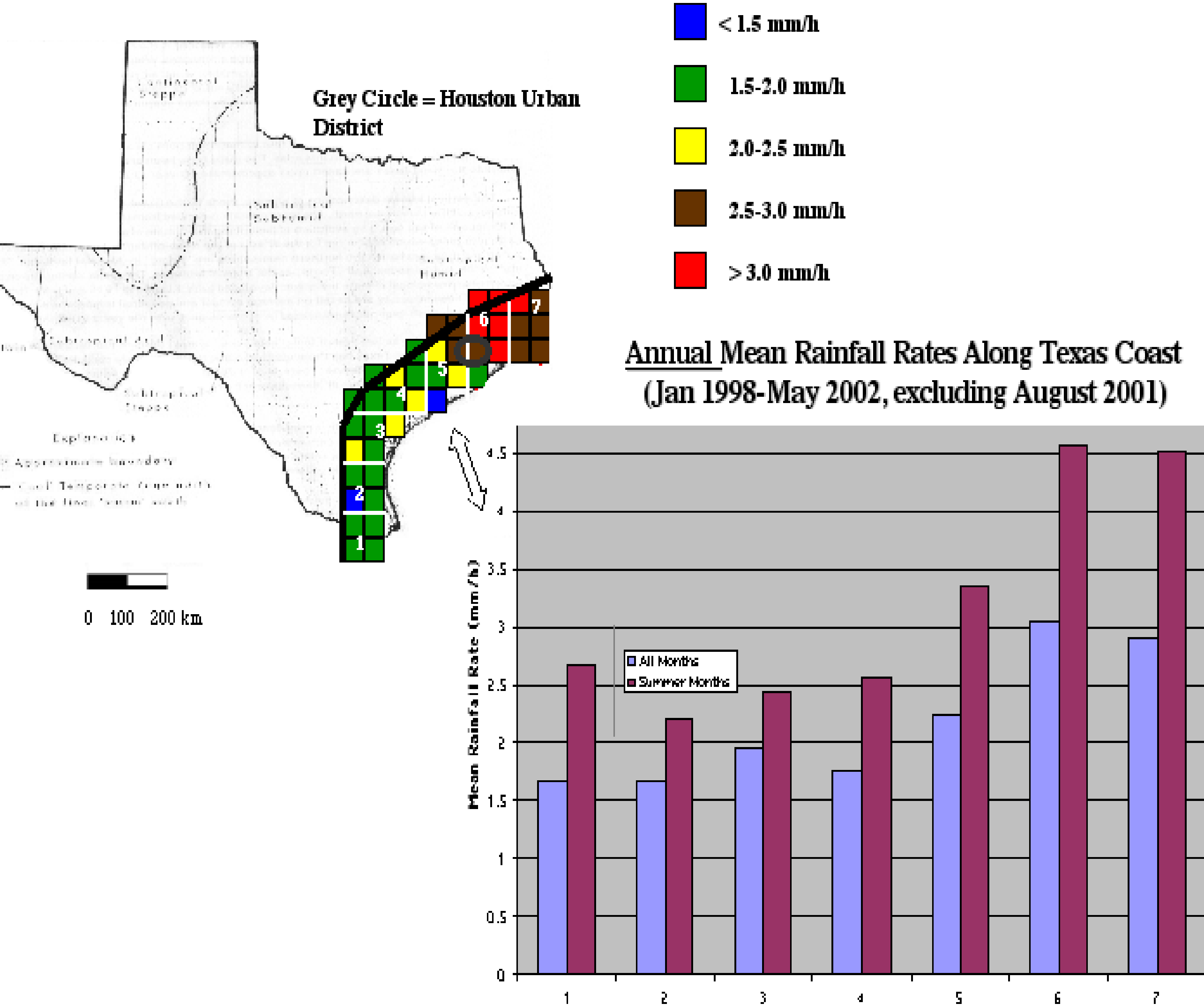

Figure 6-Mean rainfall rates over the 52-month study period (TRMM-derived) in the seven coastal zones plotted for all months and the summer.