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Popular Summary

Detection of Urban-Induced Rainfall Anomalies in Houston, Texas: A New Perspective from Space

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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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Detection of Urban-Induced Rainfall Anomalies in Houston, Texas: A New Perspective from Space

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There is increasing evidence that large coastal cities can influence weather through urban land use-weather feedbacks. This paper identifies and quantifies rainfall anomalies that are hypothesized to be linked to urbanization in the Houston area. It is one of the first efforts to quantify an urban-induced rainfall anomaly near a major U.S. coastal city and a novel application of "first of its kind", space-borne rain radar data. Results reveal annual and warm season rainfall anomalies over and downwind of Houston. Statistically significant evidence indicates that the urban heat island is a primary factor in causing the observed precipitation anomalies.

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The urban heat island (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 (1). 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 (2). 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 (3), wind patterns (4), and air quality (5).

Studies have theorized that the UHI can influence precipitation development. In the 1970s, the Metropolitan Meteorological Experiment (METROMEX) found that urban effects may lead to increased precipitation during the summer months. Increased precipitation (~5%-25% over background values) was typically observed within and 50-75 km downwind of St. Louis (6). Recent studies have continued to validate and extend the findings from METROMEX [7,8,9,10,11,12]. However, a U.S. Weather Research Panel report (13) indicated that more observational and modeling work is required because earlier results were based on a few specific cities and statistical inferences.

There is increasing evidence that large coastal cities can influence weather through urban land use-weather-climate feedbacks. In 1982, a hydrologic study (14) 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 data from 1961. They speculated that urban development in what is now the fourth largest U.S. city was the cause. Scientists at Texas A&M University (15) analyzed 12-years of ground-based lightning data and found that the highest annual and summer flash densities were over and downwind of the Houston area. Since lightning is a signature of convection in the atmosphere, urbanized Houston could also impact the distribution of rainfall.

The hypothesis established to guide this research 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 rates and amounts relative to regions upwind of the city. 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. 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 (15).

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 (16). Since Houston is located near Galveston Bay and the Gulf of Mexico, its 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 presence of the sea breeze circulation, however, we present results that support the hypothesis that urbanization in the Houston area is a primary factor causing the observed anomalies.

This paper presents results using data from the world's first satellite-based precipitation radar (PR) aboard the Tropical Rainfall Measuring Mission (TRMM) to quantify rainfall anomalies that we hypothesize to be linked to extensive urbanization in the Houston area. 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 (17). 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.

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 (18). 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.). Each 0.5° grid box contains well over 1000-2000 samples of rain occurrence for the 52-month period of this study (19). 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, it has been reported (17) 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).

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 1a is an example of the mean annual spatial distribution of rainfall rates measured by the TRMM PR 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 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 (20). Wind direction data covering the years 1979-1998 from the NCEP/NCAR reanalysis dataset (21) 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).

Analysis of the mean annual rainfall rates for Houston and surrounding areas supports the research hypothesis and is consistent with recent lightning results. In figure 1a, the orange oval (Urban Zone-UZ) covers two 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.

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. Figure 1b presents elevated lightning flash rates in the general locations of the rainfall anomalies (15). These results are consistent with recently reported "city" and downwind elevated lightning anomalies. Statistical t-tests indicate that differences are significant at 95% confidence levels (or greater).

The overwhelming consensus from the METROMEX studies of St. Louis is that urban effects on precipitation are most pronounced during the warm-season months (6). 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 2 shows the results of the summer 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 consistency with the historical work of the 1970s and more recent work. 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. 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.

Houston lies within a coastal zone and is greatly impacted by the sea-Galveston Bay breeze circulation and a complex coastline. Several investigators [22,23,24] have shown 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 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 3, 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. A numerical modeling (25) study has shown the potential convective forcing that can result from sea breeze and UHI interactions in Tokyo. 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 3.

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 interaction 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 consistent with recent lightning work 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. 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.

References and Notes

1. United Nations Population Fund. United Nations Publications, (1999).
2. T. Culliton et al, NOAA, 41 pp. (1990).
3. J. Hafner and S. Kidder, *J. Appl. Meteor.* **38**, 448 (1999).
4. M.R. Hjemfelt, M.R. *J. Appl. Meteor.*, **21**, 1239 (1982).
5. D. Quattrochi, et al., Second AMS Urban Environment Conference,104 (1998).
6. S.A. Changnon, et al , Amer. Meteor. Soc. Monogr., **18**, 81 pp. (1981).
7. R. Balling, and S. Brazel, *Theor. Appl. Climatol.*, **38**, 50 (1987).
8. E. Jauregui, and E. Romales, *Atm. Env.*, **30**, 3383 (1996).
9. R. Bornstein, and Q. Lin, *Atm. Env.*, **34**, 507 (2000).
10. J. Thielen et al., *Atm. Res.*, **54**, 15 (2000).
11. J.-J. Baik, Y.H. Kim, and H.Y. Chun, *J. Appl. Meteor.*, **40**, 1462 (2001).
12. J.M. Shepherd, H.F. Pierce, and A.J. Negri, . *J. Appl. Meteor.*, **41**, 689 (2002).
13. W.F. Dabberdt, et al. *Bull. Am. Meteor. Soc.*, **81**, 2047 (2000).
14. T. Bouvette, et al., *J. of Hydraulics Division*, Proceedings of the American Society of Civil Engineers, **Vol. 108**, 515 (1982).
15. Orville et al., *Geophys. Res. Ltr.*, **28**, 2597 (2001).
16. S. Lyons, *Mon. Wea. Rev.*, **118**, 2634 (1990).
17. C. Kummerow et al., *J. Appl. Meteor.*, **39**, 1965 (2000).
18. National Space Development Agency of Japan and National Aeronautics and Space Administration, 2000, 115 pp. (2000)
19. T. Bell, and N. Reid, *J. Appl. Meteor.*, **32**, 311 (1993).
20. B.C. Hagemeyer, *Weather and Forecasting*, **6**, 254 (1991).
21. E. Kalnay, et al., *Bull. Amer. Meteor. Soc.*, **77**, 437 (1996).
22. R.D. McPherson, *J. Appl. Meteor.*, **9**, 767 (1970).
23. A.J., Negri et al., *Bull. of Am. Met. Soc.*, **75**, 1165 (1994).
24. R.D. Baker, et al., *J. of Hydrometeor.*, **2**, 193 (2001).
25. H. Yoshikado, *J. Meteor. Soc. Japan*, **72**, 139 (1994).

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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 Captions

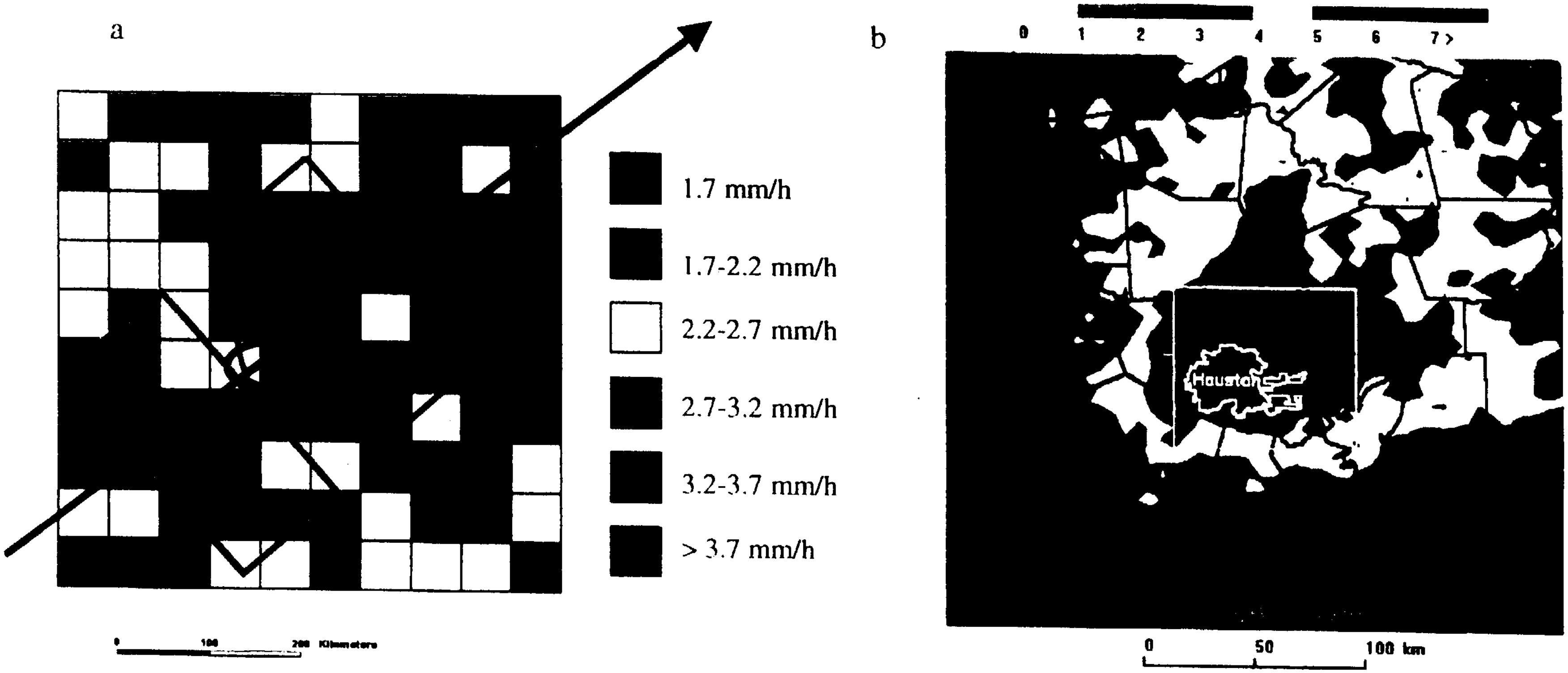
Fig. 1. a) The mean annual distribution of TRMM-derived rainfall rates from January 1998 to May 2002 (excluding August 2001). The orange oval is the approximate Houston Urban Zone and is centered on (29.75, 95.75) and (29.75, 95.25), respectively. The black vector represents the mean annual 700 hPa steering direction. The pentagon-shaped box is the "downwind urban impacted region (DUIR)" and the rectangular box is the "upwind control region (UCR)". **b)** 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 (following Orville et al. 2001).

Fig. 2. Warm season stratification of mean TRMM-derived rainfall rates over the 52 month study period (mm/h).

Fig. 3. Analysis of mean annual (from January 1998 to May 2002), TRMM-derived rainfall rates (mm/h) in the seven Texas Coastal zones 1-7(mm/h). Blue bar graph is the entire dataset. Purple bar graph is the for the warm season stratification.

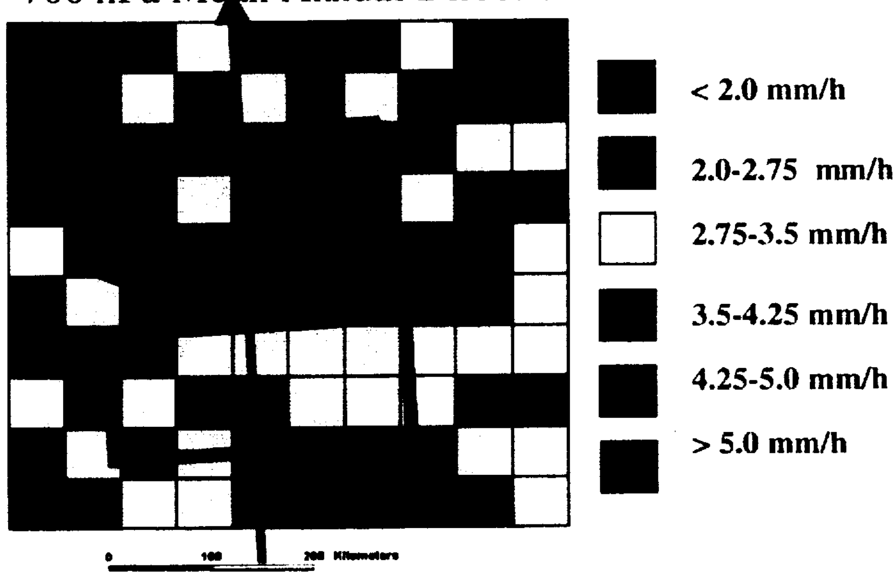
Table Captions

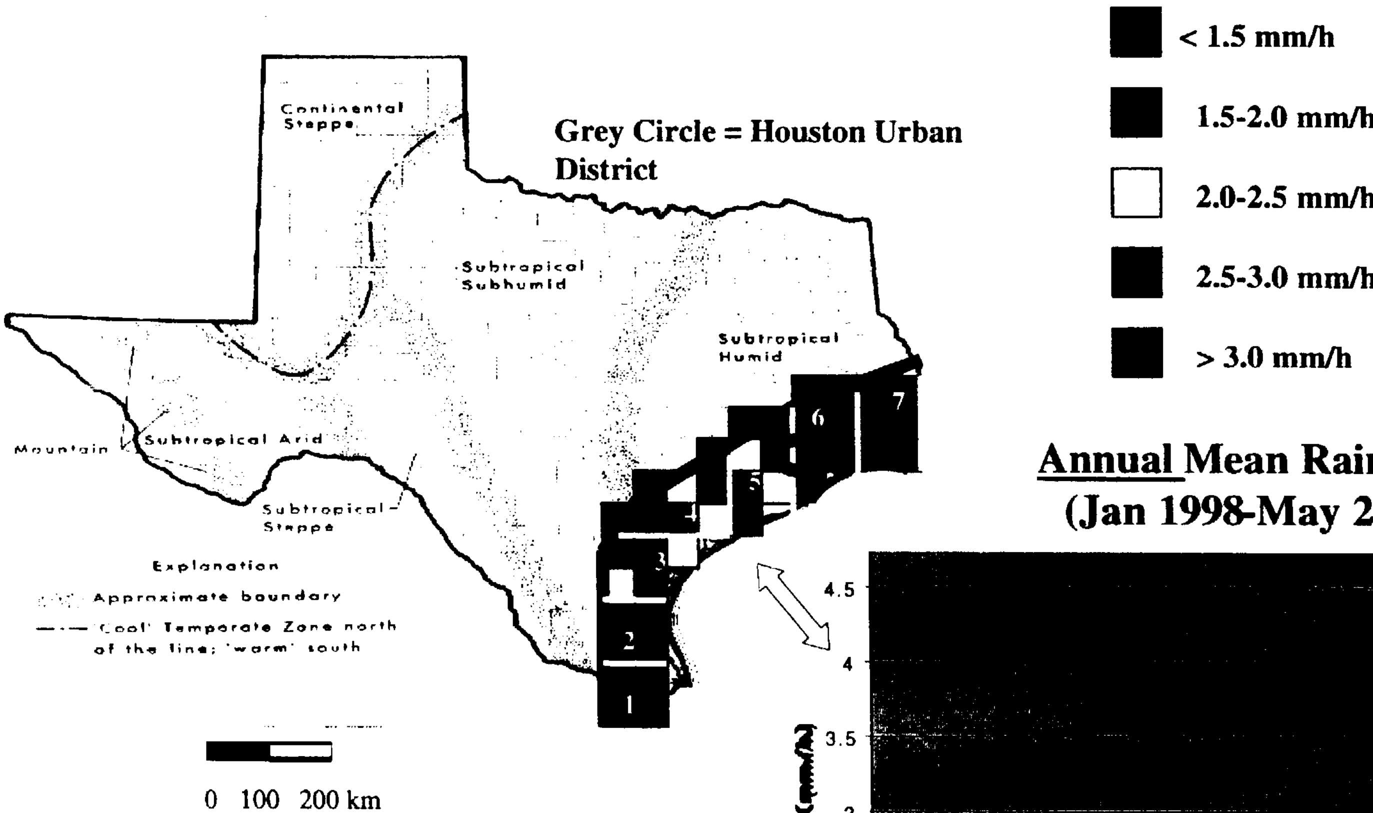
Table 1-Mean rainfall rates and relative rainfall rate variance in the upwind control region (UCR), downwind urban impacted region (DUIR), and urban zone (UZ).


a
1.7 mm/h
1.7-2.2 mm/h
2.2-2.7 mm/h
2.7-3.2 mm/h
3.2-3.7 mm/h
> 3.7 mm/h
b
0 1 2 3 4 5 6 7 >
Houston
0 50 100 km

Summer Coordinate System

700 hPa Mean Annual Direction 178°





Annual Mean Rainfall Rates Along Texas Coast (Jan 1998-May 2002, excluding August 2001)