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On Precipitation Modification by Major Urban Areas: A New Perspective from TRMM

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1. INTRODUCTION

By year 2025, 80% of the world's population will live in cities according to a 1999 United Nation's report. As cities continue to grow, urban sprawl creates unique challenges related to land use planning, transportation, agriculture, housing, pollution, and development. Urban expansion also has measurable impact on environmental process.

Urban areas modify boundary layer processes through the creation of "urban heat islands" or UHI. In cities, natural land surfaces are replaced by artificial surfaces that have very different thermal properties (e.g. heat capacity, specific heat, and thermal inertia). Such surfaces are typically more capable of storing solar energy and converting it to sensible heat. As sensible heat is transferred to the air, the temperature of the urban air tends to be 2-10 degrees higher than surrounding non-urban areas (fig, 1).

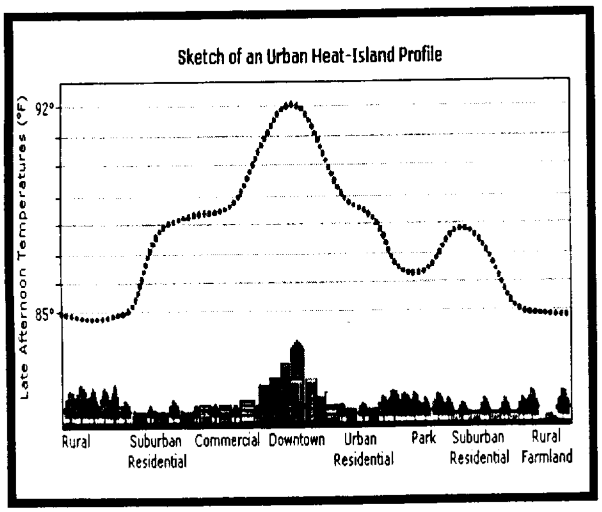

Fig.1-Typical Urban Heat Island Temperature Profile

In the past 30 years, several observational and climatological studies have theorized that the UHI can have a significant influence on mesoscale circulations and resulting convection.

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Early investigations (Changnon 1968; Landsberg 1970; Huff and Changnon 1972a and 1972b; Huff and Changnon 1973) found evidence of warm seasonal rainfall increases of 9 to 17% over and downwind of major urban 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 (Sanderson and Gorski 1978; Huff and Vogel 1978; Braham and Dungey 1978; Changnon 1979; Changnon et al. 1981; Changnon et al. 1991). Using a numerical model, Hjemfelt (1982) simulated the urban heat island of St. Louis and found positive vertical velocities downwind of the city. He suggested that the enhanced surface roughness convergence effect and the downwind shifting or enhancement of the UHI circulation by the synoptic flow were the cause (fig. 2). METROMEX results also suggested that areal extent and magnitude of urban and downwind precipitation anomalies were related to size of the urban area (Changnon 1992).

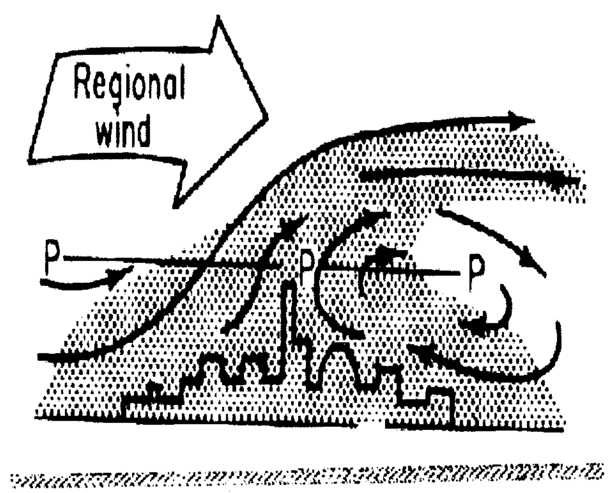

Fig. 2-Mesoscale Circulation Induced by UHI.

2. MOTIVATION and OBJECTIVES

More recent studies have continued to validate and extend the findings from pre- and post-METROMEX investigations. Balling and Brazel (1987) observed more frequent late afternoon storms in Phoenix during recent years of explosive population growth. Analysis by Bornstein and LeRoy (1990) found that New York City effects both summer daytime thunderstorm formation and movement. Jauregui and Romales (1996) observed that the daytime heat island seemed to be correlated with intensification of rainshowers during the wet season (May-October) in Mexico City. Selover (1997) found similar results for moving summer convective storms over Phoenix, Arizona. Bornstein and Lin (2000) examined data from an Atlanta meso-network to show that the UHI induced a convergence zone that initiated storms during the summer of 1999. Thielen et al. (2000) used a meso-gamma scale model to address the extent of influence of urban surfaces on the development of convective precipitation. The results showed that sensible heat fluxes and enhanced roughness due to the urban heat island can have considerable influence on convective rainfall.

The literature indicates that the signature of the "urban heat island effect" may be resolvable in rainfall patterns over and downwind of metropolitan areas. However, a recent U.S. Weather Research Program panel concluded that more observational and modeling research is needed in this area (Dabberdt et al 2000).

Objectives: Employ Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar data:

a. To validate and extend ground-based observations of climatological rainfall patterns in major urban areas using satellite rain estimates.

b. To quantify the impact of urban areas on rainfall in and downwind of cities using satellite rain estimates.

c. To demonstrate the unique capabilities and opportunities to observe multiple urban rainfall climatologies over an extensive area (38 degrees North to 38 degrees South) using the TRMM PR data.

d. To validate an unanticipated application of TRMM PR data to urban-environmental issues.

[Note: The results discussed in this section can be found on the website that accompanies this extended abstract proceeding (http://rsd.gsfc.nasa.gov/912/urban). This website contains plots, figures, and graphs with more specifics on the study.]

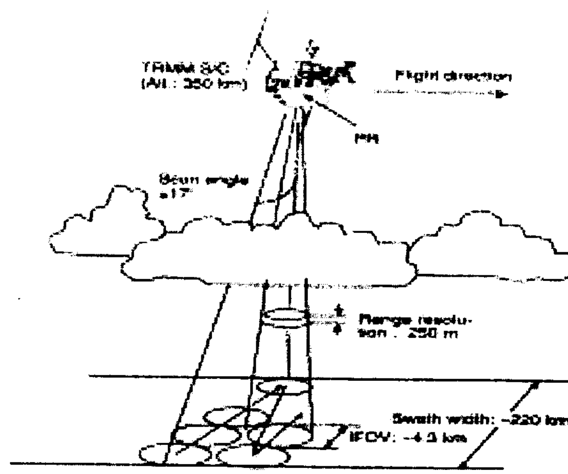

Fig. 3-TRMM Spacecraft and Scan Strategy

3. CONCLUSIONS and FUTURE WORK

The primary goal of part I of this study was to establish that a 3-year, warm season climatology of mean rainfall rates from the TRMM PR could be used to identify urban-induced rainfall anomalies. The study provides one of the first (possibly the first) published accounts of rainfall modification by urban cities that uses rainfall data from a satellite. It also illustrates a unique application of data from the first space-borne rain radar.

Prevailing wind was determined based on a 19-year climatology of geopotential heights, the results validated previous ground-based and modeling studies that identified urban-induced rainfall maxima over and downwind of cities. Using a 15-month climatology of mean rainfall rates at 2.0 km altitude, we examined the cities of Atlanta, Montgomery, Dallas, Waco, and San Antonio. We found that the average percentage increase in mean rainfall rate in the hypothesized "downwind maximum area" over the "upwind control area" was 28.4% with a range of 14.6%-51%. Over the urban area, the average change was smaller (+5.8%) but exhibited a range of –27.7%-24.7%. There was a slight indication that regions orthogonal and to the right of the mean prevailing flow (within 50 km) experienced relatively significant increases in rainfall (10.7%). However, the downwind region exhibited the most significant changes. Tabes 1 and 2 summarize key results. More extensive results can be found at the previously mentioned website.

We also demonstrated that the maximum rainfall rates found in the maximum impact area could exceed the mean value in the upwind control area by 48-116%. This maximum value was found at an average distance of 39 km from the edge of the urban center or 64 km from the exact center. The range was 20-60 km downwind of the edge of the urban center. In general, the changes in rainfall and their location relative to the "non-urban" effect regions are extremely consistent with previous work related to METROMEX and other studies. This fact provides confidence that UHI-rainfall effects are real and satellite rainfall estimates from TRMM can detect them.

Future work will be published as a separate paper. Part II of the study will seek to establish a robust validation of TRMM rainfall estimates using special rain gauge networks around the key cities in the study. We are also interested in TRMM lightning data as an additional validation source. Additionally, we will seek to address the physical mechanisms that lead to the observed "city" and downwind maxima around cities during the warm season. We will use a cloud-mesoscale model to identify the role that the UHI plays in enhancing or creating mesoscale circulations. We will also seek to differentiate whether dynamic forcing related to the mesoscale circulation (e.g. destabilizing the boundary layer, enhanced vertical motion), surface convergence due to urban roughness, or a combination of both impact warm season rainfall development. We will also propose to develop a new urban land parameterization for the cloud-mesoscale models under study at NASA-Goddard.

The implications of the research presented herein is broad. The establishment of TRMM's ability to identify rainfall anomalies associated with urban areas provides a powerful tool to investigate urban effects due to cities around the world, particularly in areas with sparse ground-based rain measurement systems. The future space-based rainfall measuring missions (e.g. Global Precipitation Measurement) will extend TRMM-like measurements to the mid-latitudes thereby extending our approach to numerous major cities not located in sub-tropical and tropical latitudes that TRMM observed. As experimental and real-time weather prediction models continue to approach smaller spatial scales, this research may require mesoscale models to consider urban surfaces and their characteristics in surface/land parameterizations. This is particularly critical as urban growth continues to infringe upon green space at alarming rates. Additionally, the research has implications for policymakers, urban planners, water resource managers, and agriculture professionals who may use an understanding of urban rainfall climatology in the design of better drainage systems, planning of land-use, or identification of optimal areas for agricultural activity. Additionally, the study further demonstrates the impact of human development on environmental processes.

References available upon request.

City	Mean Rainrate in Maximum Impact Area (mm/hr)	Mean Rainrate in Upwind Control Area (mm/hr)	Mean Rainrate over Urban Center (mm/hr)	Percentage Change in Maximum Impact Area from Upwind Control Area	Percentag Change i Urban Center A from Upwind Control A
Atlanta, Georgia	4.23	3.54	3.81	19.5%	7.8%
Montgomery, Alabama	4.39	3.83	4.39	14.6%	9.9%
Dallas, Texas	4.00	3.03	3.78	32.0%	24.7%
Waco, Texas	3.33	2.17	2.49	51.1%	14.7%
San Antonio, Texas	3.29	2.63	1.90	25.0%	-27.7%

Mean Percentage Change in Maximum Impact Area=28.4%
Mean Percentage Change in Urban Center=5.8%
Mean Percentage Change in Northern Minimum Impact Area=1.1%
Mean Percentage Change in Southern Minimum Impact Area=10.7%

Table 1.0-Mean rainrates (mm/hr) from TRMM Precipitation Radar data (2.0 km height). The data is averaged over the specified upwind, downwind, and urban area for the warm season (May-September) for 1998-2000. The percentage change from the upwind control area is given for the "maximum impact" and urban center areas. Mean percentage change for each area is also shown for all cities in the study.

City	Maximum Rainrate Value in Maximum Impact Area (mm/hr)	Percentage Change in Maximun Value in Maximum Impact Area from Upwind Control Area	Distance Downwind of Maximum Rainrate Value from Urban Center Area
Atlanta, Georgia	5.86	65.0%	~60 km
Montgomery, Alabama	5.69	48.5%	~25 km
Dallas, Texas	4.52	49.1%	~20 km
Waco, Texas	4.74	116.0%	~50 km
San Antonio, Texas	5.45	107.0%	~40 km

Maximum rainrate value is found in the maximum impact area at a mean distances of ~39 km from the edge of the urban center (or ~64 km from the exact center).

Table 2.0-Maximum 3-year warm season rainrate (mm/hr) found in the maximum impact area. The table provides information on the distance and direction from the urban center to the value in column 1.