

On Rainfall Modification by Major Urban Areas -Part I: Observations from Spaceborne Rain Radar on TRMM

J. Marshall Shepherd and Harold Pierce

To Appear in a forthcoming issue of Journal of Applied Meteorology

POPULAR SUMMARY

Almost everyone has watched a local television weather forecast. Observing the maps closely, it is noticeable that the city tends to be 2-10° F warmer than the surrounding suburbs and rural areas. This is due to the so-called "urban heat island" effect. In urban areas, there is typically a large number of buildings, roadways, cars, and artificial surfaces. The heat-retaining properties of these surfaces contribute to the formation of the "urban heat island." A good way to understand these properties is to think about how uncomfortable it is to walk on hot pavement without shoes. It is estimated that by year 2025, 80% of the world's population will live in cities. As cities continue to grow, urban sprawl creates unique problems related to land use, transportation, agriculture, housing, pollution, and development. Urban expansion also has measurable impacts on the environment.

In fact, large cities may "create" their own weather and climate. The "urban heat island" creates a wind circulation that promotes rising air over the city. During the warmer months, researchers have discovered that the rising air can produce clouds or enhance existing ones. Under the right conditions, these clouds can evolve into rain-producers or storms. It is suspected that converging air due to rougher city surfaces (e.g. buildings) also enhances rising air needed to produce rainfall. Converging air forces air upward in the same manner that two colliding cars will be forced upward upon impact. Others have suggested that increased particles in the atmosphere from cars and smokestacks in cities contribute to more efficient cloud formation. Nevertheless, early studies using ground-based instruments around cities like St. Louis, Chicago, Mexico City, and Atlanta have shown that large cities can impact rainfall over and slightly downwind of metropolitan areas. These studies were limited in many ways, however.

This study represents one of the first published attempts (possibly the first) to identify rainfall modification by cities using space-based rain measurements. The study utilizes the world's first space-based rain radar aboard NASA's Tropical Rainfall Measuring Mission (TRMM) satellite, which operates similar to the Doppler radars seen on evening newscasts. Space-based observations overcome many limitations of ground-based observations and allow for investigation of urban rainfall in numerous cities simultaneously around the world. This study suggests that major cities in the United States such as Atlanta, Dallas, San Antonio, and Nashville noticeably impact summer rainfall over and downwind of the urban centers. *By demonstrating the capability of space-borne platforms to identify rainfall changes linked to cities and urban sprawl,* the research has implications for policymakers, urban planners, water resource managers, and agriculture professionals. Such decision makers may use an understanding of urban rainfall in the design of better drainage systems, planning of land-use, or identification of optimal areas for agricultural activity. Additionally, the results may alert meteorologists that urban surfaces must be considered in the sophisticated computer models that produce weather forecasts. Finally, the study further demonstrates the impact of human development on the environmental.

J. Marshall Shepherd, Ph.D
NASA/GSFC, Code 912.0
Greenbelt, MD 20771
(301) 614-6327
shepherd@agnes.gsfc.nasa.gov

Dear Chief Editor,

I am writing to inform you of the submission of the revised manuscript, "On Rainfall Modification by Major Urban Areas -Part I: Observations from Space-borne Rain Radar on TRMM," for publication in the Articles section of Journal of Applied Meteorology.

The authors are:

Lead Author and Correspondence Author: Dr. J. Marshall Shepherd
NASA Goddard Space Flight Center
Laboratory for Atmospheres
Greenbelt, Maryland 20771
Shepherd@agnes.gsfc.nasa.gov

Second Author: Harold Pierce
Science Systems and Applications, Inc.
Laboratory for Atmospheres
Greenbelt, Maryland 20771

Date of Submission: May 1st, 2001

The manuscript has not been submitted to any other journal. We also include original copies of the figures and tables. Electronic copies (via Word files) are available, if requested.

AGREEMENT TO TRANSFER COPYRIGHT
(For non-U.S. Government)

Copyright to the article entitled "On Rainfall Modification by Major Urban Areas - Part I: Observations from Space-Borne Rain Radar on TRMM"
by J. Marshall Shepherd and Harold Pierce
assigned and transferred exclusively to the American Meteorological Society (hereinafter referred to as AMS) effective if and when the article is accepted for publication in Journal of Applied Meteorology

or in any other AMS journal in which the article may be published with the authors' consent. The authors, however, reserve 1) all proprietary rights other than copyright, such as patent rights, and 2) the right to use all or part of this article in future lectures, press releases, and reviews of their own. Certain additional reproduction rights are granted by sections 107 and 108 of the U.S. Copyright Law. All other uses will be subject to the limitations given in the copyright statement of the AMS journal in which the article is published. To be signed by all authors or if the manuscript is a "work made for hire," by the employer, who is the "legal author" under the U.S. Copyright Law.

J. Marshall Shepherd
Signature
Print name
Title if signed by employer
Date May 7, 2001
Harold Pierce
Signature
Print name
Title if signed by employer
Date May 7, 2001

Signature

Print name

Title if signed by employer

Date

Note: The form below is to be used for a work of the U.S. Government for which copyright protection is not available under Title 17, Section 105. A work of the U.S. Government is a work prepared by an officer or employee of the U.S. Government as part of this person's official duties.

CERTIFICATION OF U.S. GOVERNMENT MANUSCRIPT

The article entitled _____
by _____

is hereby certified to be a work of the U.S. Government, to have been prepared by the author(s) as officer(s) or employee(s) of the U.S. Government as part of the author(s) official duties, and therefore to be precluded from copyright protection. It is further certified that the article has not been published previously in any language and it is agreed to promptly notify the chief editor if the manuscript is submitted for publication elsewhere before its disposition by the American Meteorological Society.

Signature

Print name

Title if signed by employer, U.S. Government Agency

Date

Signature

Print name

Title if signed by employer, U.S. Government Agency

Date

Signature

Print name

Title if signed by employer, U.S. Government Agency

Date

Signature

Print name

Title if signed by employer, U.S. Government Agency

Date

On Rainfall Modification by Major Urban Areas -Part I: Observations from Space-borne Rain Radar aboard TRMM

Abstract

This study represents one of the first published attempts to identify rainfall modification by urban areas using satellite-based rainfall measurements. Data from the first space-based rain-radar, the Tropical Rainfall Measuring Mission's (TRMM) Precipitation Radar, are employed. Analysis of the data enables identification of rainfall patterns around Atlanta, Montgomery, Nashville, San Antonio, Waco, and Dallas during the warm season. Results reveal an average increase of ~28% in monthly rainfall rates within 30-60 kilometers downwind of the metropolis with a modest increase of 5.6% over the metropolis. Portions of the downwind area exhibit increases as high as 51%. The percentage changes are relative to an upwind CONTROL area. It was also found that maximum rainfall rates in the downwind impact area can exceed the mean value in the upwind CONTROL area by 48%-116%. The maximum value was generally found at an average distance of 39 km from the edge of the urban center or 64 km from the center of the city. These results are consistent with METROMEX studies of St. Louis almost two decades ago and more recent studies near Atlanta.

Future work will investigate hypothesized factors causing rainfall modification by urban areas. Additional work is also needed to provide more robust validation of space-based rain estimates near major urban areas. Such research has implications for urban planning, water resource management, and understanding human impact on the environment.

**On Rainfall Modification by Major Urban Areas -Part I: Observations from Space-borne
Rain Radar on TRMM**

Authors:

Lead Author and Correspondence Author: Dr. J. Marshall Shepherd
NASA Goddard Space Flight Center
Laboratory for Atmospheres
Greenbelt, Maryland 20771

Second Author: Harold Pierce
Science Systems and Applications, Inc.
Laboratory for Atmospheres
Greenbelt, Maryland

Date of Submission: May 1 st, 2001

1. Introduction

It is estimated that by the year 2025, 80% of the world's population will live in cities (UNFP, 1999). Figure 1 is a graphical depiction of projected urban and rural growth worldwide. As an example of urban growth, fig. 2 illustrates the rapid growth of Atlanta, Georgia. In the past 17 years, urban growth in Atlanta has spread with dramatic changes to the surrounding area. Large patches of cropland have given way to commercial and residential developments and industrialization. Researchers assembled data from Landsat satellites in the early 70's to the late 90's and created plots of growth over time. These plots provide valuable context for more detailed studies of air quality, climate changes, and urban planning. In fig.2, green and light blue regions (rural areas) yield to ever spreading red and orange regions (urban areas) over time. Cities are typically characterized by a landscape of increasing concentration of artificial surfaces such as concrete, asphalt, stone pavements, and steel. As cities continue to grow, urban sprawl (e.g., the expansion of urban surfaces outward into rural surroundings) creates unique problems related to land use, transportation, agriculture, housing, pollution, and development for policymakers. Urban expansion also has measurable impacts on environmental processes.

Urban areas modify boundary layer processes through the creation of an urban heat island (UHI). In cities, natural land surfaces are replaced by artificial surfaces that have very different thermal properties (e.g., heat capacity and thermal inertia). Such surfaces are typically more capable of storing solar energy and converting it to sensible heat. Other contributing factors to the onset of the UHI may be attributed to differences in surface albedo and anthropogenic heat release in the urban area. As sensible heat is transferred to the air, the temperature of the air in urban areas tends to be 2-10 degrees higher than surrounding non-urban areas (fig. 3). As early as the late nineteenth century,

European scientists detected the presence of UHI's in Paris, Berlin, Vienna, and London (Landsberg 1956).

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. 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 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 (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, Hjermfelt (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. 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).

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. They illustrated that radar echo maxima

were produced on the lateral edges and downwind of the city. 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. They also presented an analysis of historical records showing that frequency of intense rain showers has increased in recent decades in correlation with the growth of the 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. Their results also seemed to confirm observations from METROMEX and other studies that the UHI enhances rainfall production over and downwind of the urban area. Additionally, the model simulations suggested that stronger heat islands tended to produce more localized effects on rainfall while weaker heat islands affected rainfall at some distance downwind of the heat island.

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). In response to this recommendation, NASA and other agencies initiated programs such as the Atlanta Land-use Analysis: Temperature and Air Quality Project (ATLANTA) (Quattrochi et al. 1998). Such programs aim to identify and understand how urban heat islands impact the environment.

Previous investigations that studied urban impacts on rainfall used primarily rain gauge networks, ground-based radar, or model simulations. While useful, these studies

were limited to specific cities (e.g. St. Louis, Chicago, Washington D.C., Mexico City) with special observation networks or theoretical model simulations. Additionally, effects of topography and other factors (e.g. sea breezes, lake breezes) were often indistinguishable from the urban effects in cities examined like St. Louis (Huff and Vogel 1978). Herein, a novel approach is introduced to correlating urbanization and rainfall modification. *This study represents one of the first published attempts to identify and quantify rainfall modification by urban areas using satellite-based rainfall measurements.*

The Tropical Rainfall Measuring Mission (TRMM) is a joint NASA-Japanese Space Agency mission to study tropical rainfall and its implications for climate. However, the unique capabilities of the first space-borne rain radar (PR) enable applications beyond the stated mission objectives. Three years of mean monthly rainfall rates derived from the TRMM Precipitation Radar (PR) are employed. Analysis of PR data enables identification of rainfall patterns around major metropolitan areas of Atlanta, Montgomery, Nashville, San Antonio, Waco, Austin, and Dallas. Section 3.0 will discuss the TRMM data and research methodology employed. The study is composed of two parts. Part I (presented herein) of the study seeks to identify and quantify urban modification of rainfall using data from the TRMM PR. More specifically, the objectives are:

- 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.

The study presents a potentially useful complimentary dataset to efforts like ATLANTA and future urban-environmental impact studies. As discussed later in the text, it is beyond the scope of Part I to investigate extensive validation and modeling components. The intent of this paper is to demonstrate the ability of the TRMM spacecraft measurements to identify urban rainfall modification and corroborate previous findings in this area. A follow-on paper will address validation issues and seek answers to “cause and effect” using cloud/mesoscale models. There is a critical need for high-density rain gauge networks near cities to investigate and validate satellite measurements more thoroughly. In the future, we will propose a strategy to establish such validation sites. This article discusses the hypothesized factors for rainfall modification by cities in section 2. Section 2 also provides background on the research strategy for defining the coordinate systems, cities, and time periods of the analysis. Section 3 describes the methodology for obtaining mean monthly rainfall rates from the TRMM PR. Results of contour analyses and statistical calculations are presented in section 4. Section 5 provides a summary and concluding remarks.

2. Background and Research Strategy

a. Factors affecting rainfall by urban influences

Previous research has indicated that urban-induced changes in natural precipitation are most likely due to one or a combination of four causes. These include 1) atmospheric destabilization through the enhancement, creation, or displacement of a mesoscale circulation; 2) increased low-level convergence due to surface roughness; 3) modification of microphysical and dynamic processes by the addition of condensation nuclei; or 4) modification of the low-level atmospheric moisture content by additions from urban-industrial sources. More recently, Bornstein and Lin (2000) have suggested

that large structures such as aggregations of buildings could act to create a bifurcation zone steering storms around cities.

Figure 4 is an illustration of a typical UHI circulation and its potential interactions with prevailing wind flow. To further understand the origins of the UHI, it is instructive to examine a surface heat budget equation,

$$Q_{SW} + Q_{LW} + Q_{SH} + Q_{LE} + Q_G + Q_A = 0. \quad (1)$$

In equation (1), the terms are:

- Q_{SW} : Net short-wave irradiance.
- Q_{LW} : Net long-wave irradiance.
- Q_{SH} : Surface sensible heat flux.
- Q_{LE} : Latent turbulent heat flux.
- Q_A : Anthropogenic heat input.
- Q_G : Ground heat conduction.

At the surface, if no heat storage is permitted, differential heating results from horizontal gradients in one or more of the terms in (1). An equilibrium surface temperature is required for (1) to balance. Spatial gradients in this equilibrium temperature in conjunction with the overlying thermodynamic and moisture stratification will dominate the upward or downward flux of heat for thermally-forced systems. This will result in horizontal temperature gradients required to drive a mesoscale circulation. In the case of the UHI, the difference in surface properties of urban and rural areas leads to the differences in thermal fluxes in (1).

Vukovich and Dunn (1978) used a three-dimensional primitive equation model to show that the heat island intensity and the boundary layer stability have dominant roles in the development of heat island circulations. Additionally, Huff and Vogel (1978) found that the urban circulation is primarily enhanced by the increased sensible heat fluxes and surface roughness of the urban area. Hjelmfelt (1982) noted no observation of enhanced glaciation in urban clouds due to microphysical changes during METROMEX. Recent

research by Rosenfeld (1999) even suggests that increased aerosol amounts may reduce precipitation potential of clouds. In terms of enhancement of rainfall by moisture from industrial sources, Ochs (1975) reported that surface temperature distribution was more important than surface humidity pattern in determining the location of initial cumulus activity in his two-dimensional model simulations investigating the impact of urban surfaces. Orville et al. (1981) used simulations to show that sensible heat rather than moisture (e.g. latent heat) from nuclear power parks had a larger effect on convective clouds. Most studies seem to suggest that dynamic forcing (e.g. heat island destabilization and surface roughness) are more significant to urban rainfall modification than microphysical or moisture enhancement. More definitive research is needed in this area, however.

Addressing the factors that cause urban areas to modify rainfall is beyond the scope of this paper. Part II of the study will seek to investigate, using a cloud/mesoscale model, the relative influences of the various dynamic factors on rainfall modification. These results will be reported in a follow-on paper. This paper will assume that one or more of the stated factors influence rainfall in the urban environment. The focus of this paper is to validate and extend findings from previous ground-based observational studies by demonstrating that a new satellite-borne precipitation radar (PR) can detect precipitation anomalies related to urban areas.

b. Definition of "working" control coordinate system

To investigate the capabilities of satellite-based measurements for identifying urban effects on rainfall, we established a working hypothesis very similar in philosophy to Huff and Changnon (1972a). In their framework at each city, hypothesized areas of urban effect and no-effect on a climatological time scale were determined. Their studied identified the most frequent lower tropospheric wind flow for each city and defined the

hypothesized “downwind affected region” and upwind control regions. Our working hypothesis is a variation of this approach (see figure 5).

- Areas within a 25-kilometer radius of the city (e.g., the central urban area) will exhibit some level of enhanced precipitation due to the UHI effects.
- Areas within 25-75 kilometers downwind of the central urban area and within a 125 degree^o sector will exhibit the maximum impact (MIA) of UHI effects.
- Areas within 25-75 kilometers upwind of the central urban area are defined as the “upwind CONTROL area (UCA)”.
- Areas within ~50 square kilometers orthogonal to the mean wind vector are considered minimal to no impact regions.

In fig. 5, for example, the gray arrow represents a mean wind vector at 700 mb from the direction 270° (e.g. “westerly”). In fig. 5, the 270° vector is the horizontal reference axis (HRA) that determines the orientation of the CONTROL coordinate system. The 700 mb level was chosen arbitrarily as a representative level for the mean steering flow for convective storms and is supported by previous work in the literature (Hagemeyer 1991). In this study, the NCEP/NCAR reanalysis dataset (Kalnay et al. 1996) and published work by Hagemeyer (1991) were used to determine the mean warm season “prevailing” flow at 700 mb for the selected cities. The 700 mb geopotential height climatology from 1979 to 1998 was analyzed and summarized in table 1. For each city, the HRA is oriented according to the mean prevailing wind direction. The 125 degree sector accounts for the “steering” directions representing means that include values greater or less than the mean value; therefore, the MIA accounts for the spread of values that encompass the mean (e.g. the deviation).

c. Rationale for selected cities and time period of study

A potential shortcoming of any study that attempts to link rainfall modification with urban areas is the difficulty separating topographic and other effects (e.g. sea breeze

circulations, river breeze circulations, etc.) from urban effects. An early investigation by Huff and Changnon (1973) examined rainfall modification in eight urban areas. Two of the cities, Cleveland and Chicago, bordered major Great Lakes and possibly experienced lake breeze circulations. Two of the cities, New Orleans and Houston, were coastal and likely experienced sea breeze forcing regularly. Additionally, Washington, D.C is just east of significant topography and west of the Chesapeake Bay. St. Louis investigations, the focus of much of the METROMEX work, also had to confront issues related to topography. Huff and Vogel (1978) demonstrated some success in separating urban and topographic effects on summer rainfall distribution around St. Louis following METROMEX. Additionally, the Mississippi River and its river breeze circulations could also impact mesoscale circulations near St. Louis. These factors suggest caution when considering urban circulations against other mesoscale-induced circulations.

The cities chosen for this study (see table 1) are Atlanta, Georgia; Montgomery, Alabama; Dallas, Texas; Waco, Texas; Austin, Texas and San Antonio, Texas. Nashville, Tennessee was also examined, however, observational restraints of the satellite (section 3.0) and data contamination (section 4.0) rendered this site with incomplete data. Each city was selected because it was 1) located between TRMM's 38N and 38S latitudinal bound; 2) relatively flat; 3) not located near major topography or major water/land boundaries; and 4) representative of an urban area with clearly distinguishable urban and rural zones.

The study also focused only on the warm season months, defined as May to September of 1998-2000. The three-year period reflects the current availability of TRMM data at the time of writing. Changnon et al. (1991) found some evidence that St. Louis could alter precipitation in the fall, winter, and spring. However, the overwhelming consensus from METROMEX and other efforts is that urban effects are most pronounced during warm season months (Huff and Changnon 1972; Changnon et

al. 1991; Jauregui and Romales 1996). The most likely reason for pronounced urban effects during the warm season is the reduction of larger scale synoptic forcing. Advection associated with relatively strong synoptic flow tends to eliminate the thermal differentiation between rural and urban areas (Pielke and Segal, 1996). Additionally, synoptic forcing like frontal systems tend to mask mesoscale circulations during the cool season. During the warm season, the UHI-induced mesoscale circulation is more dominant and can significantly alter boundary layer processes.

3. Data and Methodology

One of the true novelties of this study is the application of TRMM data to the problem of rainfall modification by urban areas. *An exhaustive review of the literature has revealed no study (to the author's knowledge) employing satellite-derived rainfall data to the urban rainfall modification problem.* This study utilizes a unique satellite dataset from TRMM which 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. As a part of NASA's Earth System Enterprise, TRMM seeks to understand the mechanisms through which changes in tropical rainfall influence global circulation. Additionally, a goal is to improve ability to model these processes in order to predict global circulations and rainfall variability at monthly and longer time scales. Such understanding has implications for assessing climate processes related to El Nino/La Nina and Global Warming.

Over the past 3 years, the complementary suite of instruments aboard TRMM (i.e., TRMM Microwave Imager, Visible Infrared Spectroradiometer, Lightning Imaging Sensor, Precipitation Radar and CERES) has contributed significantly towards reducing uncertainty in satellite estimates of rainfall in the Tropics, where almost 67% of the Earth's rain falls. TRMM has provided knowledge related to the climatology,

seasonality, and variation of tropical rainfall; the mesoscale structure of rain-producing systems; and the physics of precipitation.

TRMM has contributed significant and unexpected knowledge to understanding the structure and morphology of hurricanes by providing hurricane "cat scans" of the inner mechanisms of the storms as well as providing sea surface temperature measurements in cloud and cloud-free environments. TRMM has provided unique perspectives on the global distribution of lightning and confirming that land-based thunderstorms are electrically-active. TRMM related efforts to assess global latent heating is proving to show positive impact on mesoscale to global weather/climate models. Additionally, TRMM is providing new perspectives on El Nino/La Nina, tornadic thunderstorms, and the effects of pollution on rainfall. Herein, we demonstrate the capability of the high-resolution TRMM PR data to detect rainfall modification associated with urbanization. Future studies (and missions) will address validation issues related to the urban problem. However, the results presented herein are compelling and provide exciting first steps.

The TRMM PR operates at a frequency of 13.8 GHz and can achieve quantitative rainfall estimation over land as well as ocean. The observation concept of the TRMM PR is presented in figure 6. 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. Because TRMM is in a precessing low-inclination (35°), low-altitude orbit, it is particularly suited for capturing rainfall events at temporal scales of 1 month or greater (e.g. climatological records).

In this study, we utilize space-time averaged PR rainfall products to investigate rainfall modification due to urban effects. We primarily conduct analysis on mean monthly rainfall rates (mm/hr) at a height level of 2.0 km in 0.5 degree x 0.5 degree cells. These rainfall rates were calculated as a part of the 3A25 algorithm suite. Figure 7 is the TRMM PR algorithm flow (NASDA/NASA 2000). In the diagram, unprocessed receiver

counts are converted to calibrated received power. The radar equation (2) and conversion equations (3) are then used to convert PR received power into radar reflectivity factor:

$$Pr(\text{range}) = \frac{p^3 |K|^2 Pt * Gr * abng * cross * c * pulse}{2^{10} 1r2 * wavelength^2 * range^2} Zm \quad (2)$$

$$dbZm = 10 \log \left(10^{(ps/10)} - 10^{(Pn/10)} \right) - C + 20 \log(\text{range}) \quad (3)$$

In equations (2) and (3), the following variables are used:

$$C = Pt + Gt + Gr + 10\log(\text{along} \times \text{cross}) + 10\log(c \times \text{pulse}) - 20\log(\text{wavelength}) + C_0$$

Pt:	transmitter power
Pulse:	transmitter pulse width
Gt:	transmit antenna gain
Gr:	receive antenna gain
along:	along track beam width
cross:	cross track beam width
c:	speed of light
C ₀ :	radar constant

The final step in the processing involves converting reflectivity to rainfall estimates using the attenuation-corrected Z-profiles and an equation of the form $R=aZ^b$ in which a and b are both functions of the rain type, existence of bright-band, freezing height, storm height, and absolute height. Effects of the difference in the raindrop size distribution by rain type, the phase state, the temperature, and the difference in terminal velocity due to changes in the air density with height are also taken into account. The coefficient a is further modified by an index of uniformity (NASDA/NASA, 2000). Figure 8 is an example of a mean monthly 0.5° rainfall map for June 2000 centered over the Texas region.

For more detailed analysis, the mean rainfall rate value at each grid point was calculated over the three-year period (1998-2000) for the months of May, June, July, August, and September. For a given point, a total of 15 mean monthly rainfall rate values were averaged (3 years \times 5 months of data). Effectively, this procedure establishes a 15-month climatology of PR rainfall rates for the years 1998-2000. It is important to remember that monthly rainfall rates at each gridpoint are aggregates of numerous pixels defined as “rainy” by the algorithm over the 30-day period. Finally, the mean values were placed in Cartesian coordinates and contoured using a simple 3-point smoother in the GEMPAK contour analysis (NASA, 1990).

Additionally, an analysis of a parameter called the Urban Rainfall Ratio (URR) was conducted. The URR is defined as

$$URR = \frac{R_i}{R_{BG}} \quad (4)$$

R_i represents a given mean rainfall rate at a gridpoint. R_{BG} is the mean background value. This value is the average of all mean rainfall rates in the entire CONTROL coordinate system in fig. 5. It encompasses values in the upwind control, maximum impact, minimum impact, and urban areas. Essentially, the URR is a measure of the relative magnitude of a given point to a background value. In the analysis, a value greater (less) than 1.0 is considered a positive (negative) anomaly.

4. Results

a. Overview analysis of southeastern cities

Analysis of the data reveals interesting findings that are provocative and consistent with previous studies that employed ground measurements or numerical models. In fig. 9, a GOES-IR (channel 2 3.9 micron) image of the southeastern United States is placed next to the GEMPAK analysis of the 15-month rainfall rate climatology. Examining the GOES-image in fig. 9a, it is revealed that the arrows indicate thermal signatures

associated with urban heat islands in Atlanta, Montgomery, and Nashville. This evidence confirms the existence of significant heat islands with these urban areas. In fact, Atlanta has been the recent focus of intensive study related to urban heat islands.

Recent work from Project ATLANTA by Bornstein and Lin (2000) discovered that urban heat islands create thunderstorms in southern quadrants of the city. Figure 10 is taken from Bornstein and Lin (2000) and illustrates the rainfall amount for an urban-initiated storm in Atlanta (ATL). The rainfall amounts were calculated from a special network of high density rain gauge networks placed around Atlanta during the 1996 Summer Olympics. Examining fig. 9b, the TRMM data indicate a relative maximum in warm season rainfall rates slightly southeast of the city. The location of the relative maximum is fairly consistent with the placement of UHI-induced rainfall anomalies such as those reported by Bornstein and Lin (2000). It should be noted that the underlying dataset in figs. 9b and 11b is from NASA's LANDSAT-5 spacecraft. In the figure, values contoured in red (blue) represent values of at least 4.2 mm/day (less than or equal to 3.6 mm/day). A re-examination of fig. 5 and table 1 validates our hypothesis that based on a mean "steering flow direction" of 273 degrees, maximum impact from urbanization would be expected downwind of the city (within the 125 degree sector). The relative maximum in fig. 9b falls within the MIA. Figure 9b. also illustrates relatively smaller rainfall rates west and north of the city as we hypothesized. *Our results in fig. 9b seem to corroborate findings near Atlanta using a special rain gauge network and provide some degree of confidence that TRMM rainfall estimates are robust.* However, it is acknowledged that more high density rain gauge networks are needed the cities in future components of this research.

Montgomery, Alabama (MGM) is a smaller urban area than Atlanta, but fig. 9a illustrates that it can still generate an urban heat island. The TRMM data further suggests that Montgomery's UHI exerts an influence on rainfall. From table 1, the mean

“steering” wind over Montgomery was 266 degrees in the warm season. Based on our hypothesis, the maximum impact area or MIA should be east of the city and within the 125 degree sector. Examining fig. 9b, relatively high rates are found in the MIA while relatively low values are found west and north of the city.

There is also evidence that rainfall is maximized in the MIA of Nashville, Tennessee (mean “steering” wind of 282 degrees). However, we excluded Nashville (BNA) from the analysis because there was insufficient data to compute upwind CONTROL area (UCA) values since Nashville is near the northern latitudinal extent of TRMM coverage.

Table 2.0 provides a more quantitative assessment of how the various sectors of our hypothesized CONTROL coordinate system varied in terms of rainfall rates around Atlanta and Montgomery. *Table 2.0 indicates that the mean rainfall rates in the MIA for Atlanta and Montgomery were greater than the UCA by 19.5% and 14.6%, respectively. This number is consistent with finding by Huff and Changnon (1973) who found warm seasonal rainfall increases of 9 to 17% for large cities. The data also indicate smaller increases directly over the urban area for Atlanta (7.8%) and Montgomery (9.9%) which suggests a greater propensity towards enhancement downwind of the city.*

b. Overview analysis of Texas cities

In fig. 11, we examine data from urban areas in Texas. As in fig. 9, fig. 11a is a GOES IR image illustrating the significant urban heat island signatures associated with urban centers along the Interstate 35 corridor. These cities include Dallas, Waco, Austin, and San Antonio. The heat signatures clearly identify the urban development along the I-35 transportation corridor. The urban heat island signature for Houston is also apparent.

Interestingly, an examination of fig. 11a indicates that the 15 month rainfall rate climatology from TRMM reveals relative maxima ~30-100 km east and northeast of Dallas (DFW), Waco (ACT), Austin (AUS) and San Antonio (SAT). At the same time, relatively minimal rainfall rates are found west of these cities. In fact, the rainfall

maxima were strong identifiers of the cities and I-35 corridor before overlaying navigation markers or underlying Landsat-5 data. It is also interesting to observe the two rainfall maxima to the east and west of Galveston Bay (near Houston (HOU)). It can be argued that at least one of these maxima has UHI influences, however, it is difficult and beyond the scope of this paper to differentiate impacts related to the sea breeze circulation. A recent paper by Orville et al. (personal communication) to be published suggests that strong convergence patterns over Houston may be linked with the urban heat island. Houston is not included in our analysis but will be examined in future work.

Table 1.0 revealed that the mean prevailing “steering” flow for Dallas, Waco, and San Antonio were 225°, 210°, and 198°, respectively. Using our CONTROL coordinate system, it is found that the relative maxima in figure 11b are all located in the downwind MIA. In table 2, results indicate that the mean rainrate in the MIA (Urban Center) for Dallas was 32% (24.7%) greater than the UCA. For Waco, the mean rainrate in the MIA (Urban Center) was 51.1% (14.7%) greater than the UCA. Consistent results are found for San Antonio with the mean rainrate in the MIA (Urban Center) exhibiting a difference of 25.5% (-27.7%) over the UCA. Though not included in the table, results revealed that the mean rainrate in the MIA (Urban Center) for Austin was 68% (41%) larger than over the UCA. Portions of the MIA for Austin and San Antonio overlap so we chose to focus on the larger metropolitan area of San Antonio. It is likely that Austin exerts significant influence on UHI-induced rainfall, however.

In order to evaluate the significance of the differences in warm season rainfall rates between the upwind CONTROL area and hypothesized effect areas, statistical *t*-tests were applied. The *t*-test gives the probability that the difference between the mean of two groups is caused by chance rather than some forcing or circumstance. It is customary to establish that if this probability is less than 0.05, the difference is significant and not caused by chance. Significance testing indicate the following:

- Major Impact Area vs Upwind CONTROL Probability = 0.034.
- Urban Area vs Upwind CONTROL Probability=0.805.

These findings suggest that differences between the MIA and the Upwind CONTROL are significant. The probability is less conclusive for the urban area although the probability is still fairly small. *Nevertheless, the statistical analysis confirms that our major finding of a downwind bias is significant and not likely due to random chance.*

c. General summary of results

The results corroborate early METROMEX findings and later studies from ground observations that suggested a downwind maximum in rainfall relative to major urban cities. *For the five cities studied, the average 3-year, warm season climatology of rainfall rates were 28.4% larger in the downwind "maximum impact area" than the upwind CONTROL area defined.* The rates were 5.8% greater over the urban city. This value increases to 14.2% if the negative value for San Antonio is discounted. In the minimum impact area to the left (right) of the prevailing wind vector, rainfall rates were 1.1% (10.7%) greater than the UCA.

The results suggest a definite bias towards greater enhancement in the downwind regions of the urban area with minimal enhancement directly over the city and orthogonal to the prevailing wind vector. This downwind bias is also apparent in analysis of the Urban Rainfall Ratio defined in equation 4. Figure 12 is a plot of URR for all gridpoints in the CONTROL coordinate system for all five cities in the study. Blue circles represent URR values located in the downwind maximum impact region. Red squares represent URR values located in the upwind CONTROL area. Green plus marks represent URR values in the minimum impact areas. Black stars represent URR values over the urban area. A review of figure 5 may be helpful. *The most interesting result from fig. 12 is that 70% of the values above a reference value of 1.0 (i.e., the threshold for positive anomalies) are found in the downwind maximum impact area. An examination of fig. 12*

also reveals that the majority of upwind CONTROL points (76%) have URR values less than 1.0. These results indicate the downwind bias towards increased rainfall rates. The majority of the points in the minimum impact area fall below URR values of 1.0 also. URR values over the urban center are generally cluster close to 1.0 which suggests minor impact over the city. However, the important finding verifies the tendency towards higher rates downwind of the city. In previous studies (Landsberg 1970; Changnon 1968; Huff and Changnon 1973; Sanderson and Gorski 1978; Changnon et al. 1991; Thielen et al. 2000), it was found that summer precipitation values in and downwind of the city reflected increases of 5%-25% over background values. This is quite consistent with the range of 5.8%-28.4% in the TRMM climatology and the analysis of URR values in fig. 12.

The next question of interest is to determine how far downwind the primary urban-influenced rainfall maxima occur. Huff and Changnon (1972) found that rainfall within a radius of 50-75 miles of St. Louis was impacted by the city. Thielen et al. (2000) noted that METROMEX investigators reported enhancement over and at a distance of 40 km downwind of St. Louis. Thielen et al. (2000) also reported that in their "urban" model simulation rainfall was focused over and 60—80 km downwind of the urban surface.

To investigate the distance factor using the 3-year TRMM climatology, we identified the location and distance of the maximum rainfall rate found in the maximum impact area (downwind) of each city. These results are listed in table 3.0. Because table 3.0 lists maximum values in the MIA not the mean values, a better indication is given of how much larger downwind rainfall values can be. *In general, the maximum value is greater than the mean value of the upwind CONTROL area by a range of 48.5%-116%. Also, the maximum value lies in the MIA at distances ranging from 20-60 km from the edge of the urban area (45-105 km from the exact center). Overall, the maximum value is found in the MIA at a mean distance of 39 km from the edge of the urban enter or 64 km from the*

exact center. Again, these values are very consistent with findings from previous investigators. Figure 13 is a schematic summary of the general location and distance of the area near each city that seemed to exhibit urban-impacted rainfall modification.

5. Summary and Conclusions

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.

Recalling that 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.

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.

Acknowledgements: The authors would like to thank Dr. Ramesh Kakar and Dr. Robert Adler for providing support for this research through NASA's TRMM Project. The authors would also like to thank Dr. Dennis Chesters for valuable insight on GOES images. We are also grateful to Dr. David Starr for his guidance in this project. Finally, we are grateful to our colleagues who agreed to review this manuscript and provide valuable comments and suggestions.

6. References

- Balling, R., and S. Brazel, 1987: Recent changes in Phoenix summertime diurnal precipitation patterns. *Theor. Appl. Climatol.*, **38**, 50-54.
- Bornstein, R., and M. Leroy, 1990: Urban barrier effects on convective and frontal thunderstorms. Preprint volume, Fourth AMS Conference on Mesoscale Processes, Boulder, CO. 25-29 June.
- Bornstein, R., and Q. Lin, 2000: Urban heat islands and summertime convective thunderstorms in Atlanta: three cases studies. *Atm. Env.*, **34**, 507-516.
- Braham, R.R., Jr., and M. Dungey, 1978: A study of urban effects on radar first echoes. *J. Appl. Meteor.*, **17**, 644-654.
- Changnon, S.A., 1968: The LaPorte weather anomaly-fact or fiction? *Bull. Amer. Meteor. Soc.*, **49**, 4-11.
- _____, 1979: Rainfall changes in summer caused by St. Louis. *Science*, **205**, 402-404.
- _____, 1992: Inadvertent weather modification in urban areas: Lessons for global climate change. *Bull. Amer. Meteor. Soc.*, **73**, 619-627.
- _____, F.A. Huff, P.T. Schickedanz, and J.L. Vogel. 1977: Weather anomalies and impacts: In summary of METROMEX Vol. I, Ill. State Water Survey, Bull. 62, Champaign, 260 pp.
- _____, R.G. Semonin, A. H. Auer, R.R. Braham, and J. Hales, 1981: *METROMEX: A Review and Summary*. Amer. Meteor. Soc. Monogr., **18**, 81 pp.
- _____, R.T. Shealy, and R.W. Scott, 1991: Precipitation changes in fall, winter, and spring caused by St. Louis. *J. Appl. Meteor.*, **30**, 126-134.
- Dabberdt, W.F., J. Hales, S. Zubrick, A. Crook, W. Krajewski, J. C. Doran, C. Mueller, C. King, R.N. Keener, R. Bornstein, D. Rodenhuis, P. Kocin, M.A. Rossetti, F. Sharrocks, and E.M. Stanley, 2000: Forecast issues in the urban zone: Report of the 10th prospectus development team of the U.S. Weather Research Program. *Bull. Am. Meteor. Soc.*, **81**, 2047-2064.

- Hagemeyer, B.C., 1991: A lower-tropospheric thermodynamic climatology for March through September: Some implications for thunderstorm forecasting. *Weather and Forecasting*, **6**, 254-270.
- Hjemfelt, M.R., 1982: Numerical simulation of the effects of St. Louis on mesoscale boundary layer airflow and vertical motion: Simulations of urban vs. non-urban effects. *J. Appl. Meteor.*, **21**, 1239-1257.
- _____, 1986: Urban hydrological review. *Bull. Am. Meteor. Soc.*, **67**, 703-712.
- Huff, F. A., and S.A. Changnon, 1972a: Climatological assessment of urban effects on precipitation at St. Louis. *J. Appl. Meteor.*, **11**, 823-842.
- _____, and _____, 1972b: Climatological assessment of urban effects on precipitation, Part II. Final Report, NSF Grant GA-18781, Illinois State Water Survey, Urbana, 237 pp.
- _____, and _____, 1973: Precipitation modification by major urban areas. *Bull. Amer. Meteor. Soc.*, **54**, 1220-1232.
- _____, and J.L. Vogel, 1978: Urban, topographic and diurnal effects on rainfall in the St. Louis region. *J. Appl. Meteor.* **17**, 565-577.
- Jauregui, E., and E. Romales, 1996: Urban effects on convective precipitation in Mexico City. *Atm. Env.*, **30**, 3383-3389.
- Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, A. Leetma, R. Reynolds, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, R. Jenne, and D. Joseph, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, **77**, 437-471.
- Landsberg, H.E., 1956: The climate of towns. *Man's Role in Changing the Face of the Earth*, University of Chicago Press, 584-603.
- _____, 1970: Man-made climate changes. *Science*, **170**, 1265-1274.

- National Space Development Agency of Japan and National Aeronautics and Space Administration, 2000: Tropical Rainfall Measuring Mission Precipitation Radar Algorithm: Instruction Manual Version 2.0, 115 pp.
- National Aeronautics and Space Administration, 1990: GEMPAK5 User's Manual.
- Ochs, H.T., III, 1975: Modeling of cumulus initiation in METROMEX. *J. Appl. Meteor.*, **14**, 873-882.
- Orville, H.D., P.A. Eckhoff, J.E. Peak, J.H. Hirsch, and F.J. Kopp, 1981: Numerical simulation of the effects of cooling tower complexes on clouds and severe storms. *Atmos. Environ.*, **15**, 823-835.
- Pielke, R.A., and M. Segal, 1986: Mesoscale circulations forced by differential terrain heating, *Mesoscale Meteorology and Forecasting*, Ed. Peter S. Ray., AMS, Boston, 793 pp.
- Quattrochi, D., J. Luvall, M. Estes, C. Lo, S. Kidder, J. Hafner, H. Taha, R. Bornstein, R. Gillies, and K. Gallo, 1998: Project Atlanta (Atlanta Land use Analysis: Temperature and Air Quality): a study of how urban landscape affects meteorology and air quality through time. Preprint Volume. Second AMS Urban Environment Conference, Albuquerque, NM, pp. 104-107.
- Rosenfeld, D., 1999: TRMM observed first direct evidence of smoke from forest fires inhibiting rainfall. *Geophysical Research Letters*, **26**, 3105-3108.
- Sanderson, M., and R. Gorski, 1978: The effect of metropolitan Detroit-Windsor on precipitation. *J. Appl. Meteor.*, **17**, 423-431.
- Selover, N., 1997: Precipitation patterns around an urban desert environment-topographic or urban influences? Association of American Geographers Convention, Fort Worth, TX, 25-29 May 1997.
- Thielen, J., W. Wobrock, A. Gadian, P.G. Mestayer, and J.-D. Creutin, 2000: The possible influence of urban surfaces on rainfall development: a sensitivity study in 2D in the meso-gamma scale. *Atm. Res.*, **54**, 15-39.
- UNFP, 1999: *The State of World Population 1999*. United Nations Population Fund. United Nations Publications, New York, 76 pp.

Vukovich, F. M., and J. W. Dunn, 1978: A theoretical study of the St. Louis heat island: Some parameter variations. *J. Appl. Meteor.*, **17**, 1585-1594.

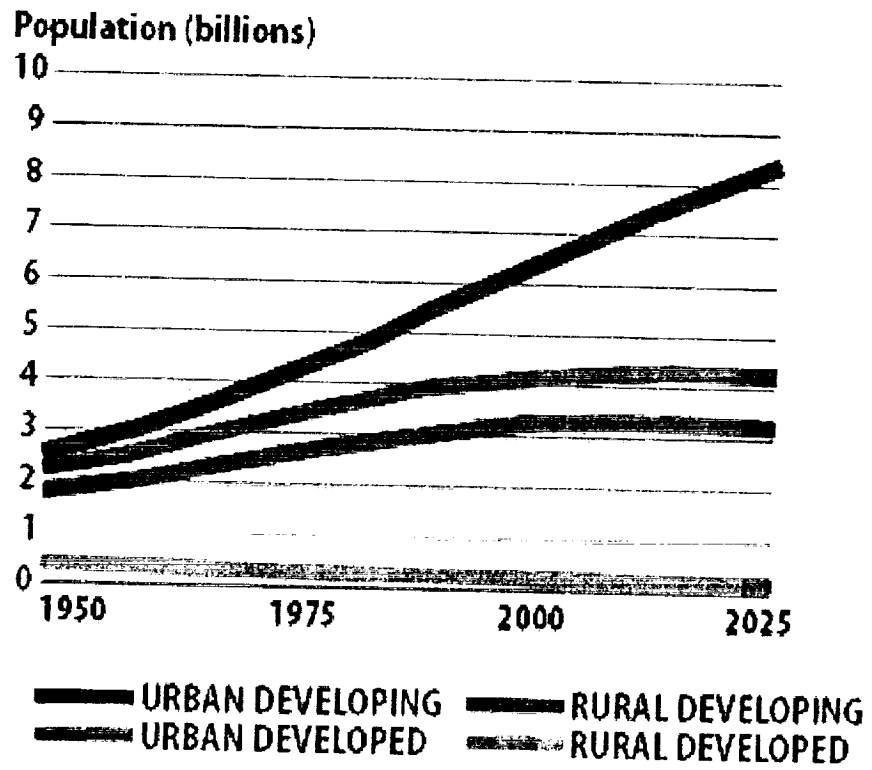
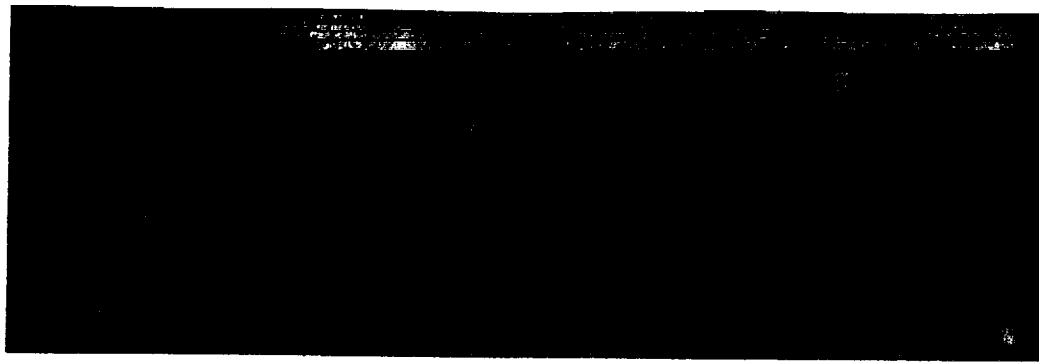


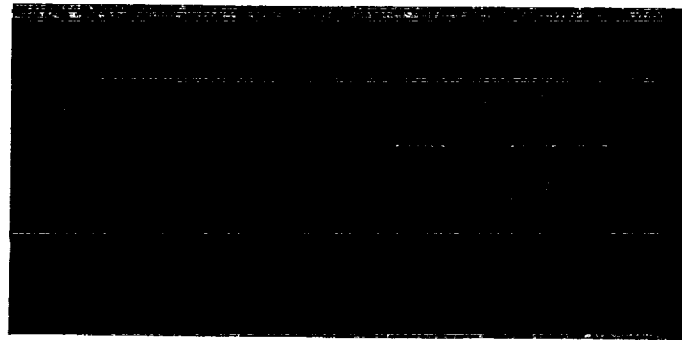
Fig.1. Projected growth of urban and rural areas over the next two decades.



1973

1979

1987



1992

1997

Fig. 2. Landsat depiction of the rapid growth of the metropolitan Atlant area over the past two decades.

Sketch of an Urban Heat-Island Profile

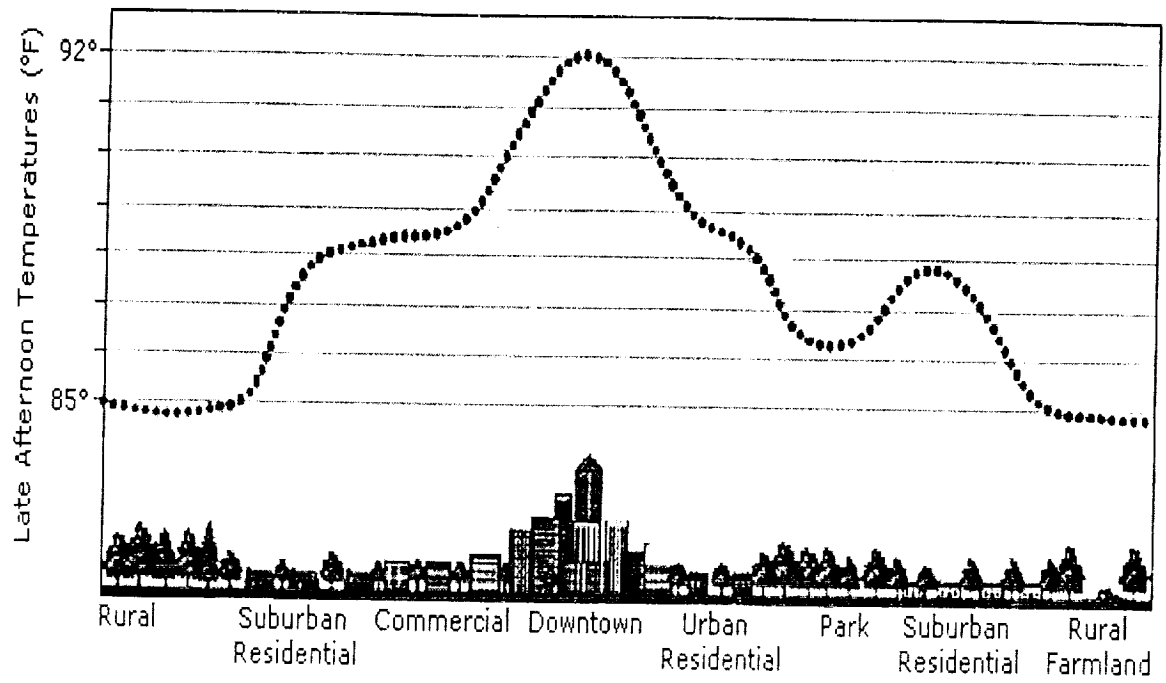


Fig. 3. Typical urban heat island temperature profile.

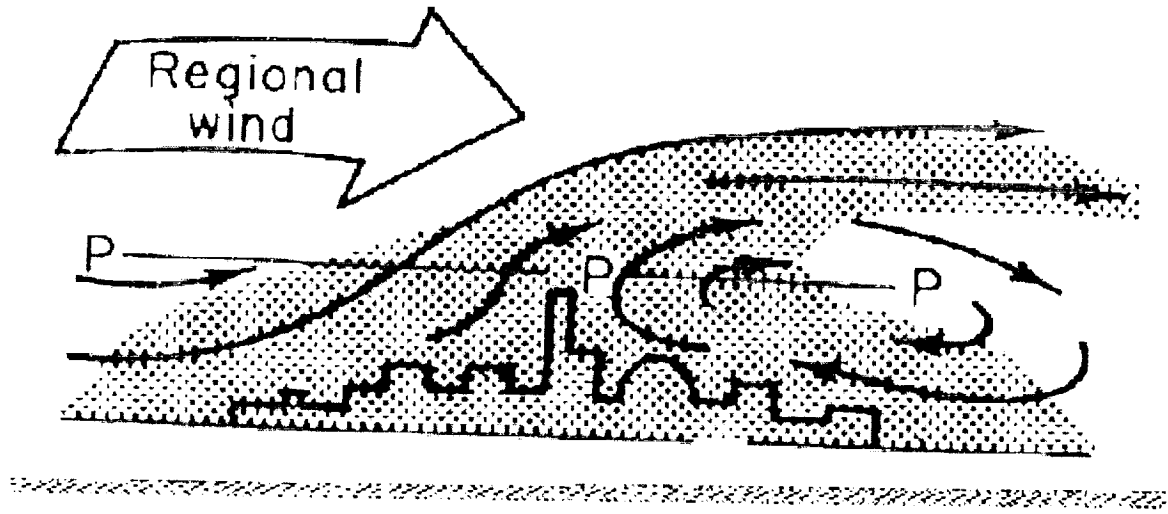
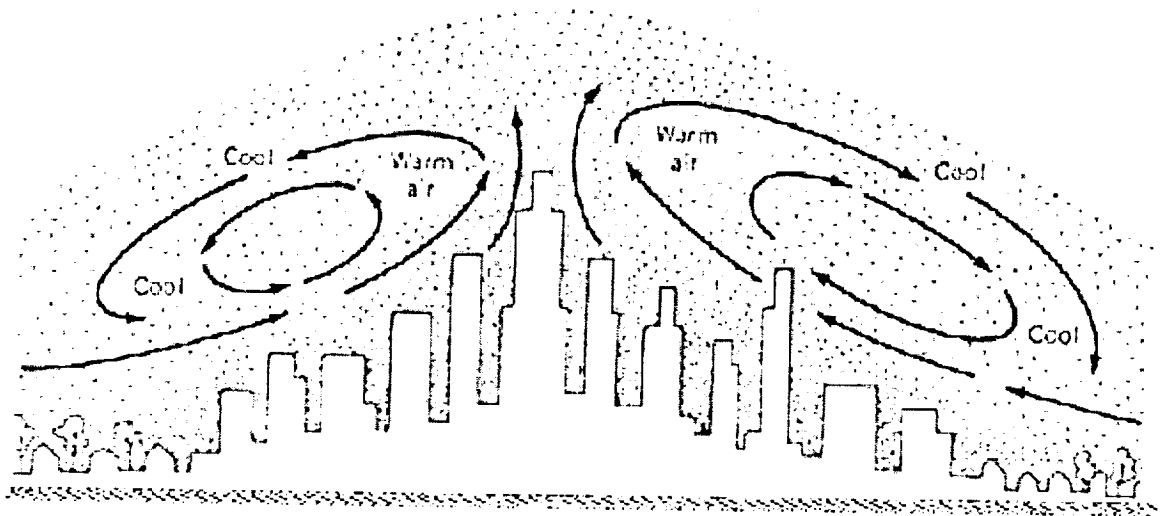


Fig. 4. Typical urban heat island circulation and its potential interaction with the prevailing wind flow.

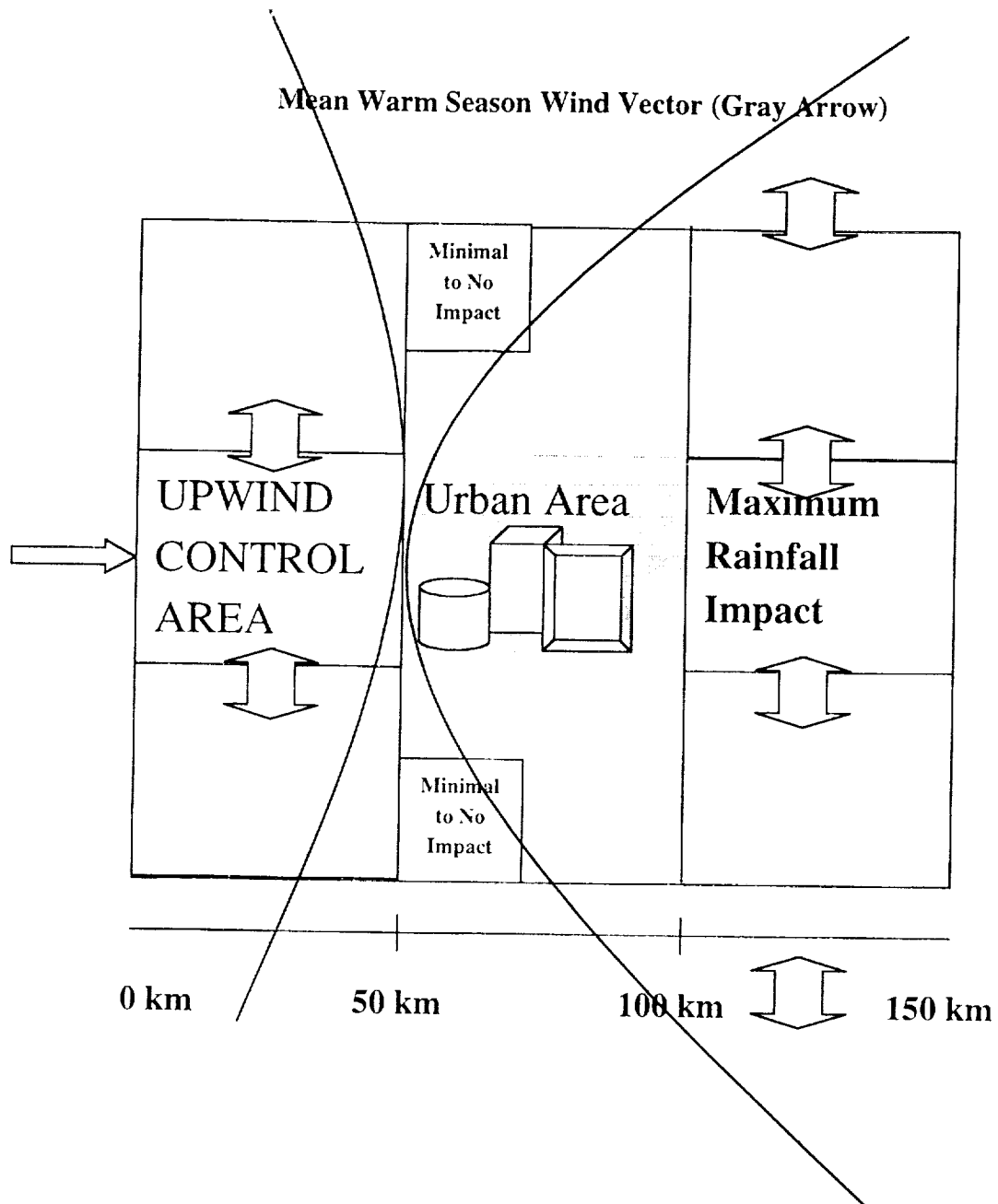


Fig. 5. Theoretical coordinate system used to define upwind control, urban, and maximum UHI-rainfall impact area. Gray arrow depicts the mean prevailing wind and defines the reference axis for the coordinate system.

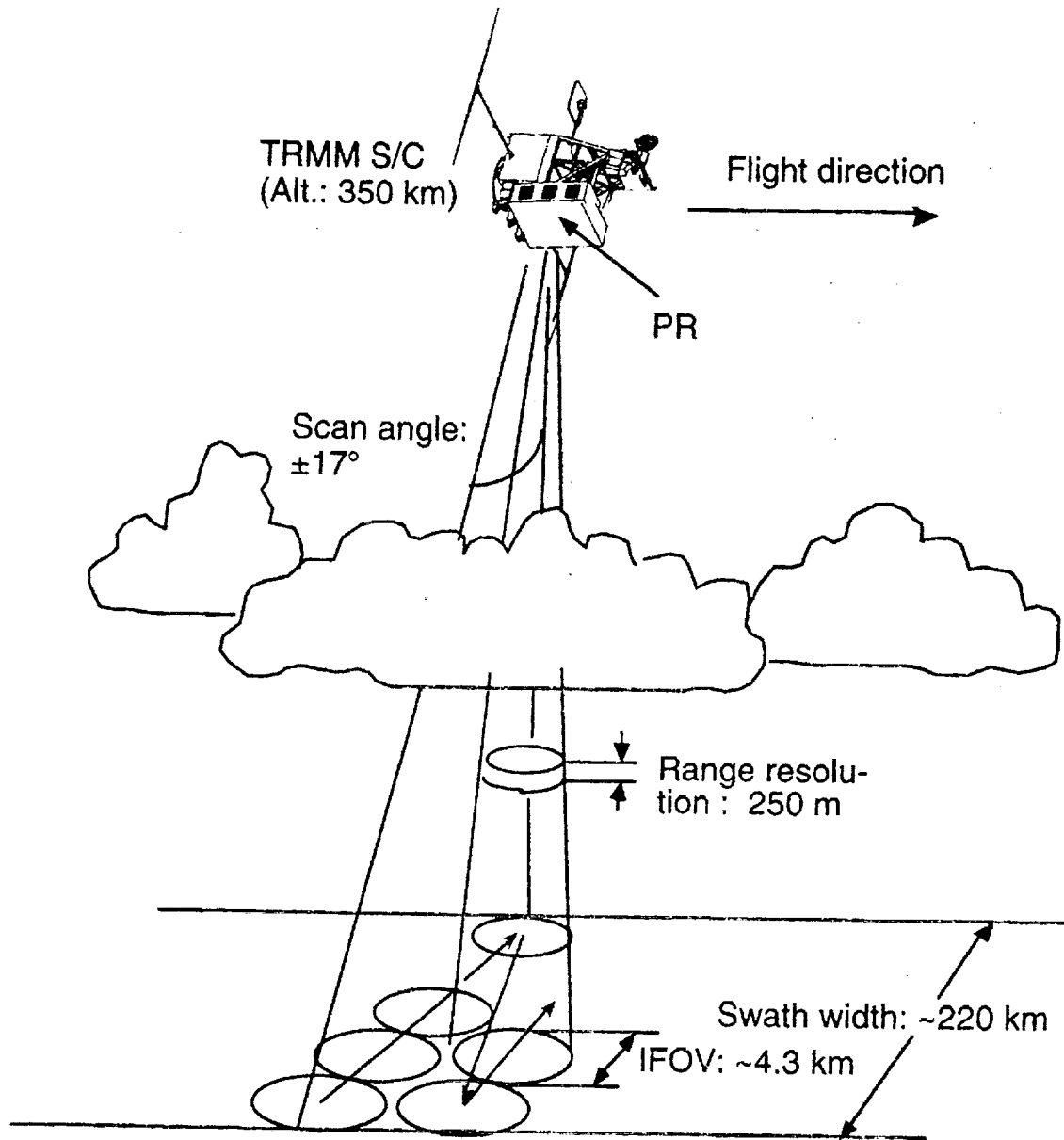


Figure 0-1. Observation concept of the PR.

Fig. 6. Schematic of TRMM platform scan strategy.

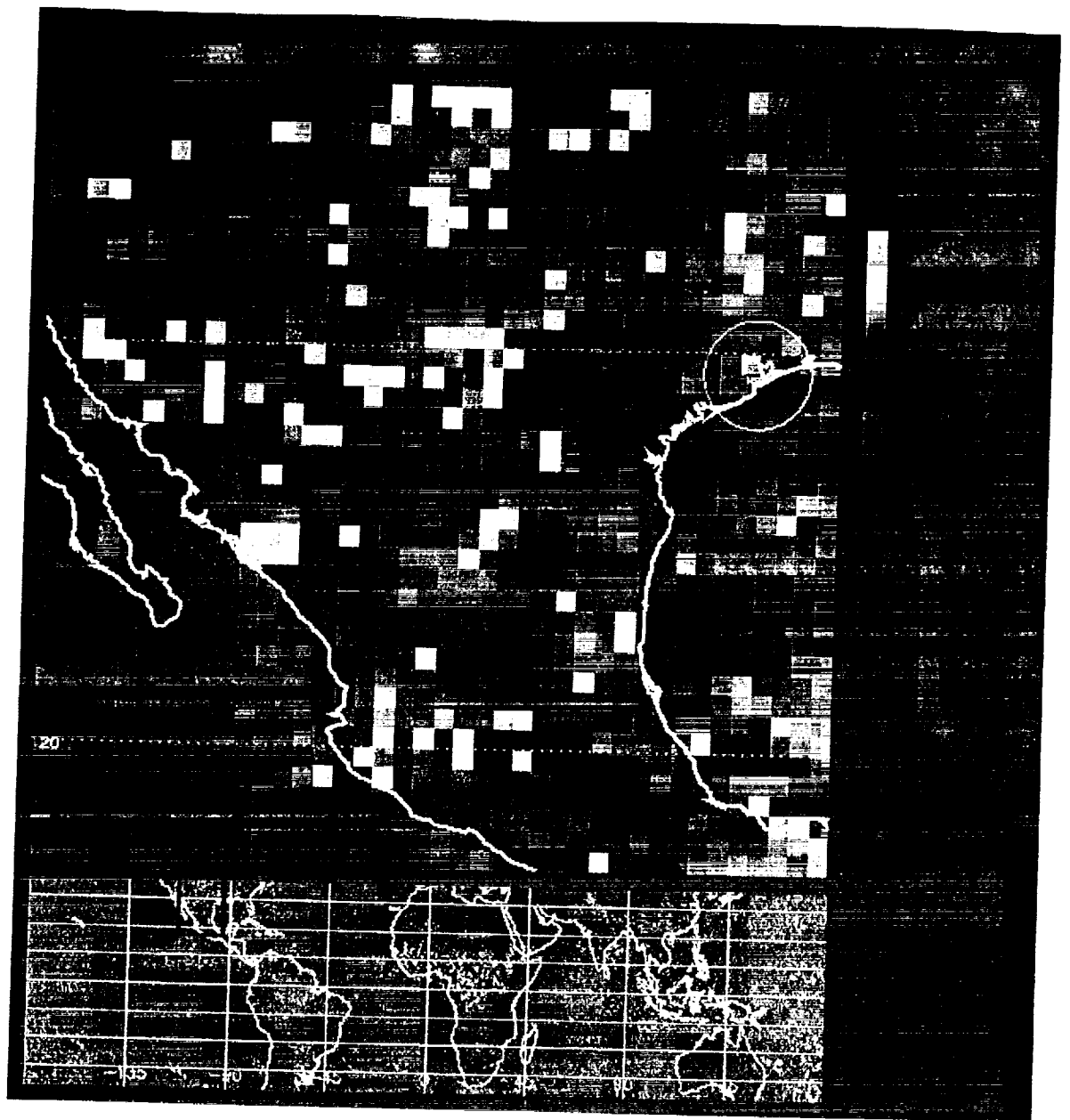


Fig. 8. Mean rainfall rates at 2.0 km. The bottom panel illustrates global rainfall rates for June 2000 using the 3A25 algorithm. The top panel is focused on a region centered over Texas. Blue shades represent values from roughly 0.0-2.0 mm/hr. Darker shades of green represent values from 2.0-5.0 mm/hr. Light shades of green represent values ranging from 5.0-8.00 mm/hr. Shades of tan and yellow represent values ranging from 8.0-16.0 mm/hr. Orange and red values between 16.0-100.0 mm/hr.

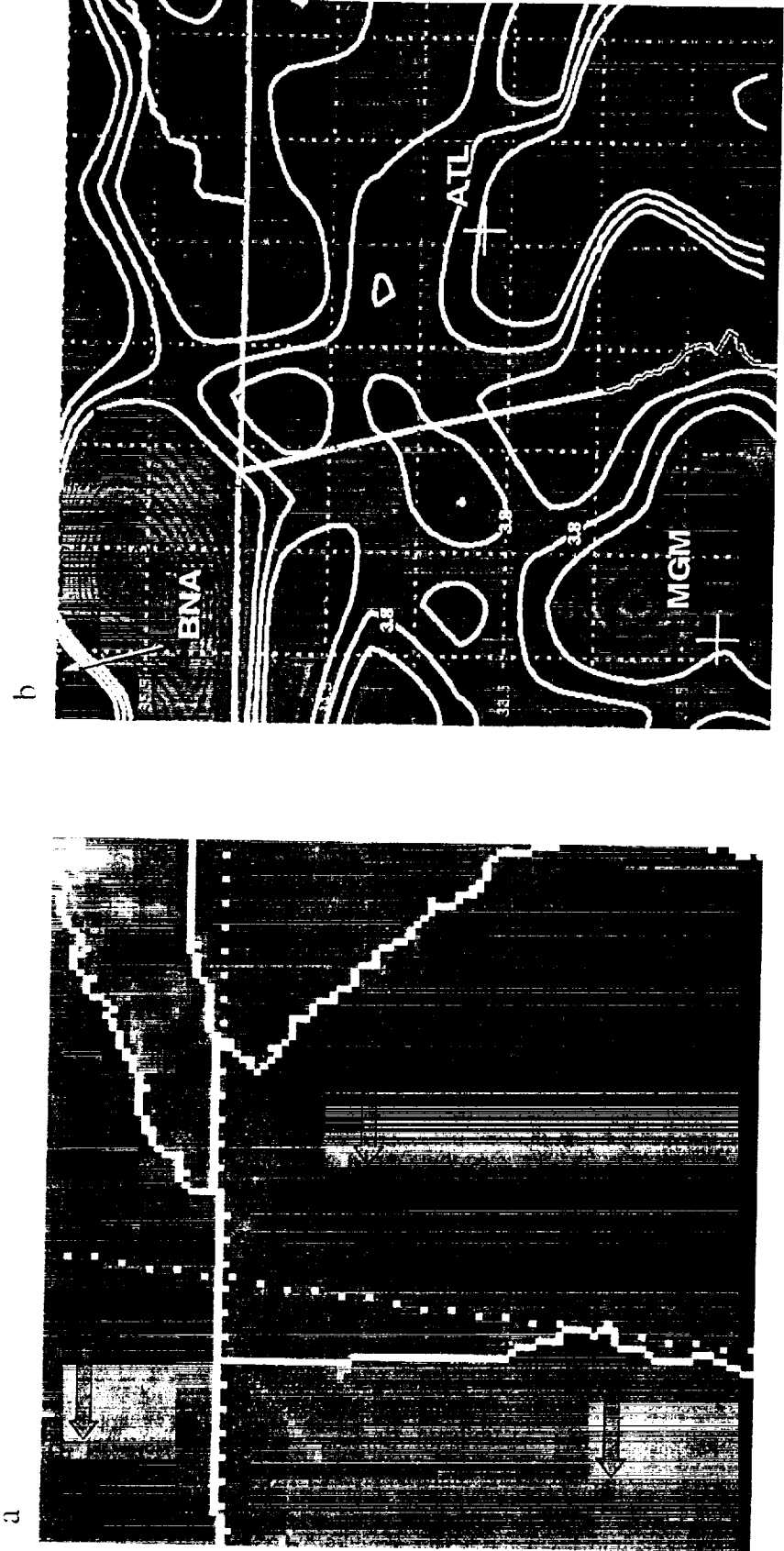


Fig. 9a-b. Fig. 9a is a GOES IR 3.9 micron image of the southeast. Urban heat islands for Nashville, Montgomery, and Atlanta are indicated as dark warm regions by the arrows. Fig. 9b represents a contour plot of the 15-month, warm season climatology of mean rainfall rates at 2.0 km using half-degree TRMM PR data. Values in red are greater than or equal to 4.2 mm/hr. Values in blue are less than or equal to 3.6 mm/hr.

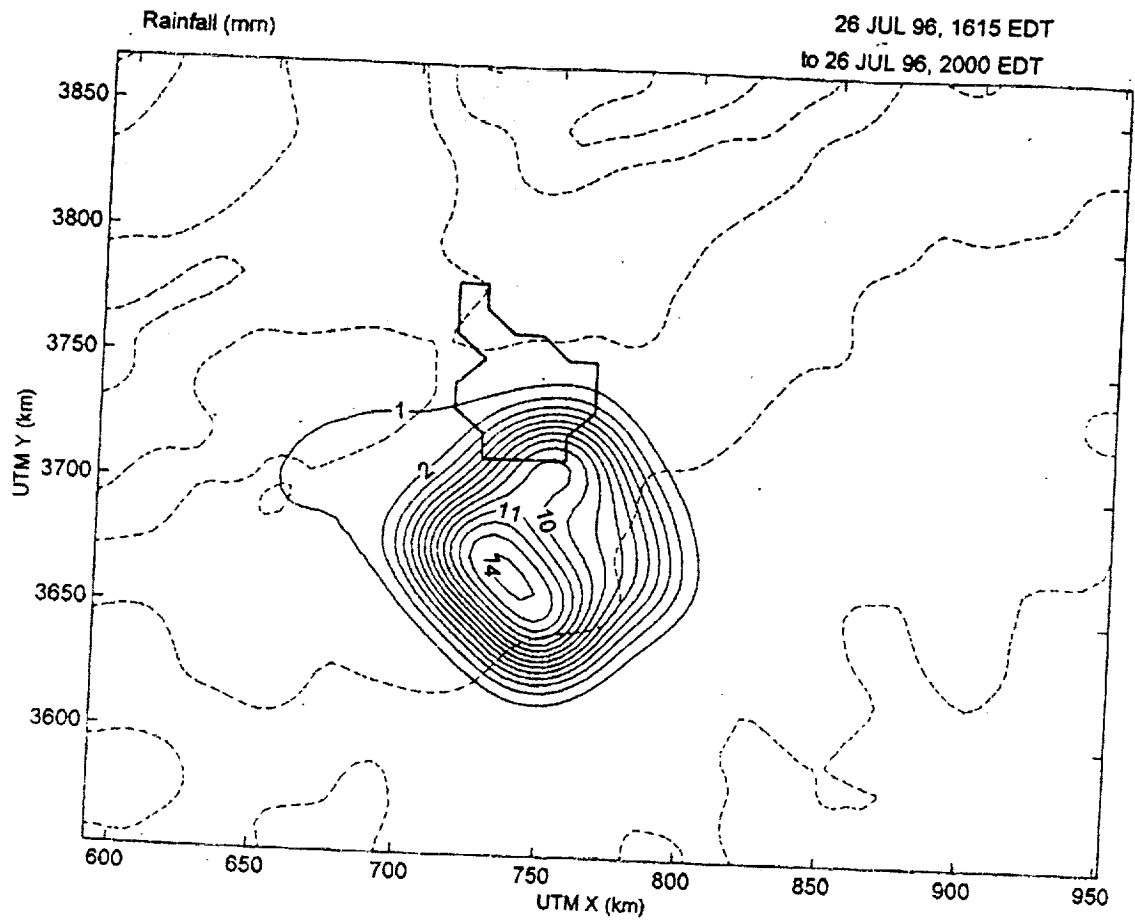
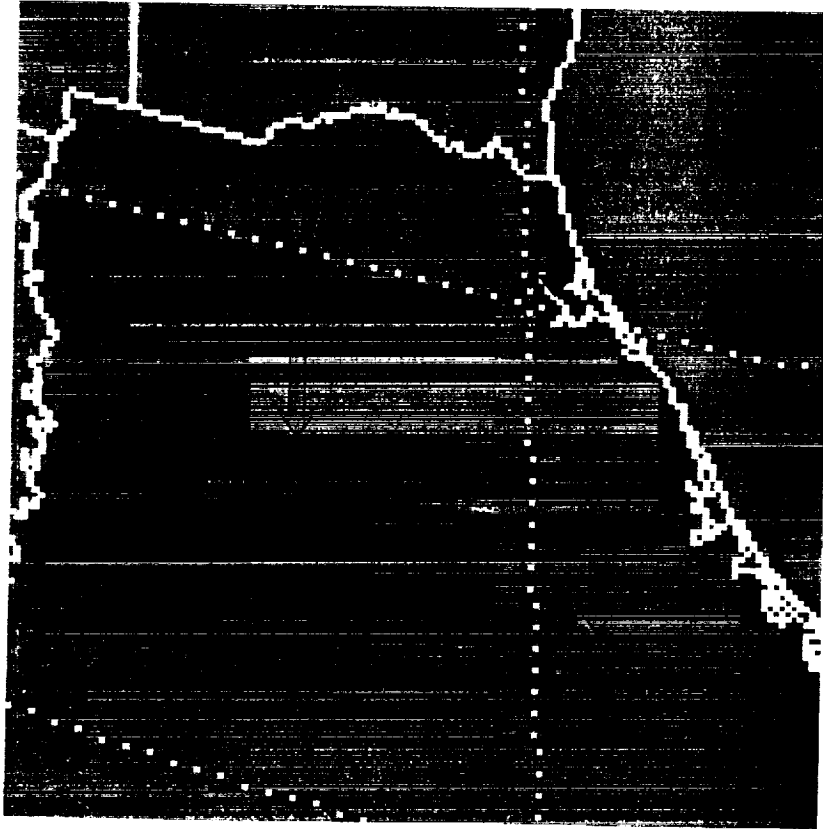


Fig. 10. Rainfall amount (increment of 1 mm) analysis for a typical Urban Heat Island Induced rainstorm on July 26th, 1996 (following Bornstein and Lin, 2000).

a



b

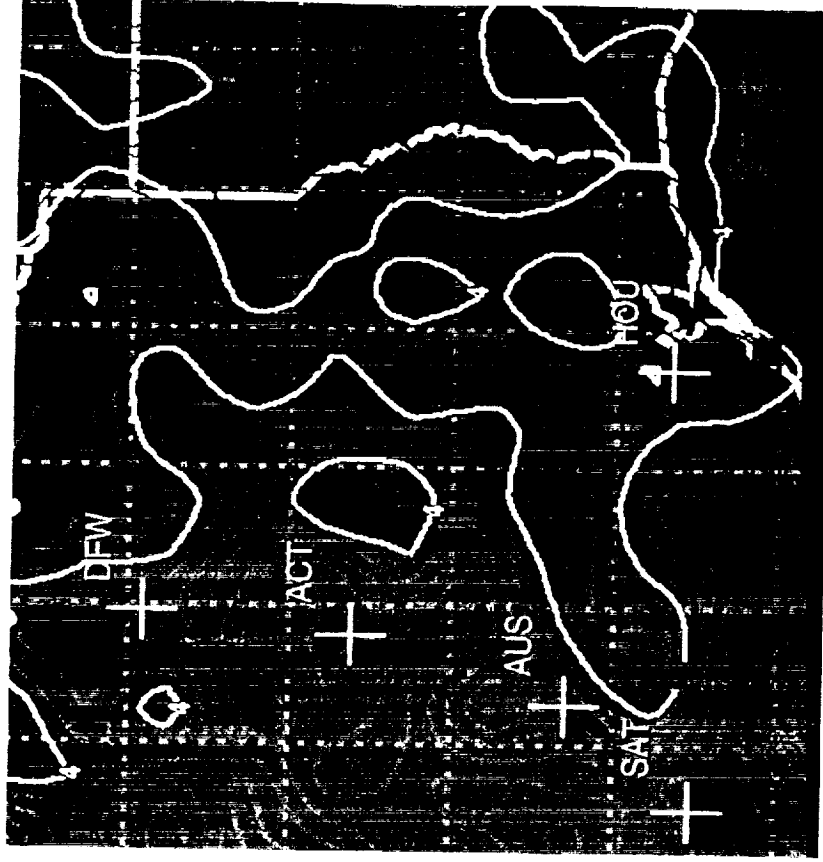


Fig. 11a-b. Fig. 11a is a GOES IR 3.9 micron image of Texas. Urban heat islands for Dallas, Waco, Austin, San Antonio and Houston are indicated as warm, dark regions by the arrows. Fig. 11b represents a contour plot of the 15-month, warm season climatology of mean rainfall rates at 2.0 km using the half-degree TRMM PR data. Values in red are greater than or equal to 4.2 mm/hr. Values in blue are less than or equal to 3.6 mm/hr.

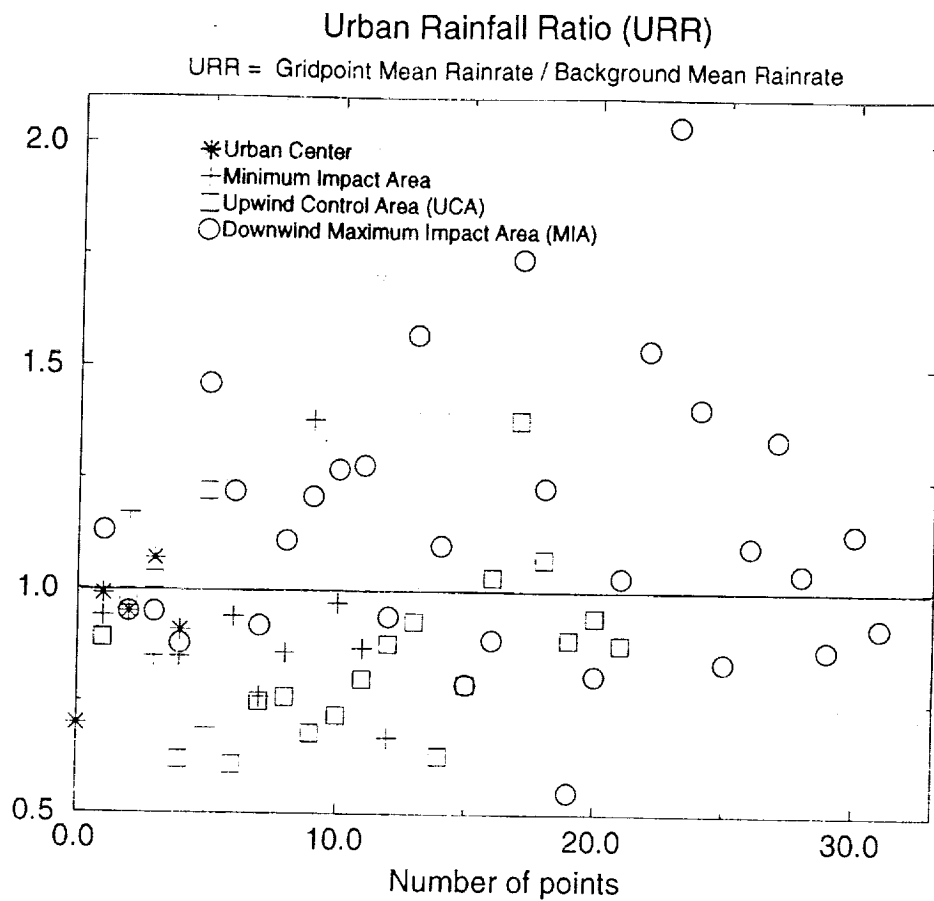


Fig. 12. Urban Rainfall Ratio (URR) for gridpoints in the CONTROL coordinate system for the five cities in the study. Blue circles represent URR values located in the downwind maximum impact area (MIA). Red squares represent URR values located in the upwind control area (UCA). Green plus marks represent URR values in the one of the minimum impact areas. Black stars represent URR values over the urban area (see figure 5).

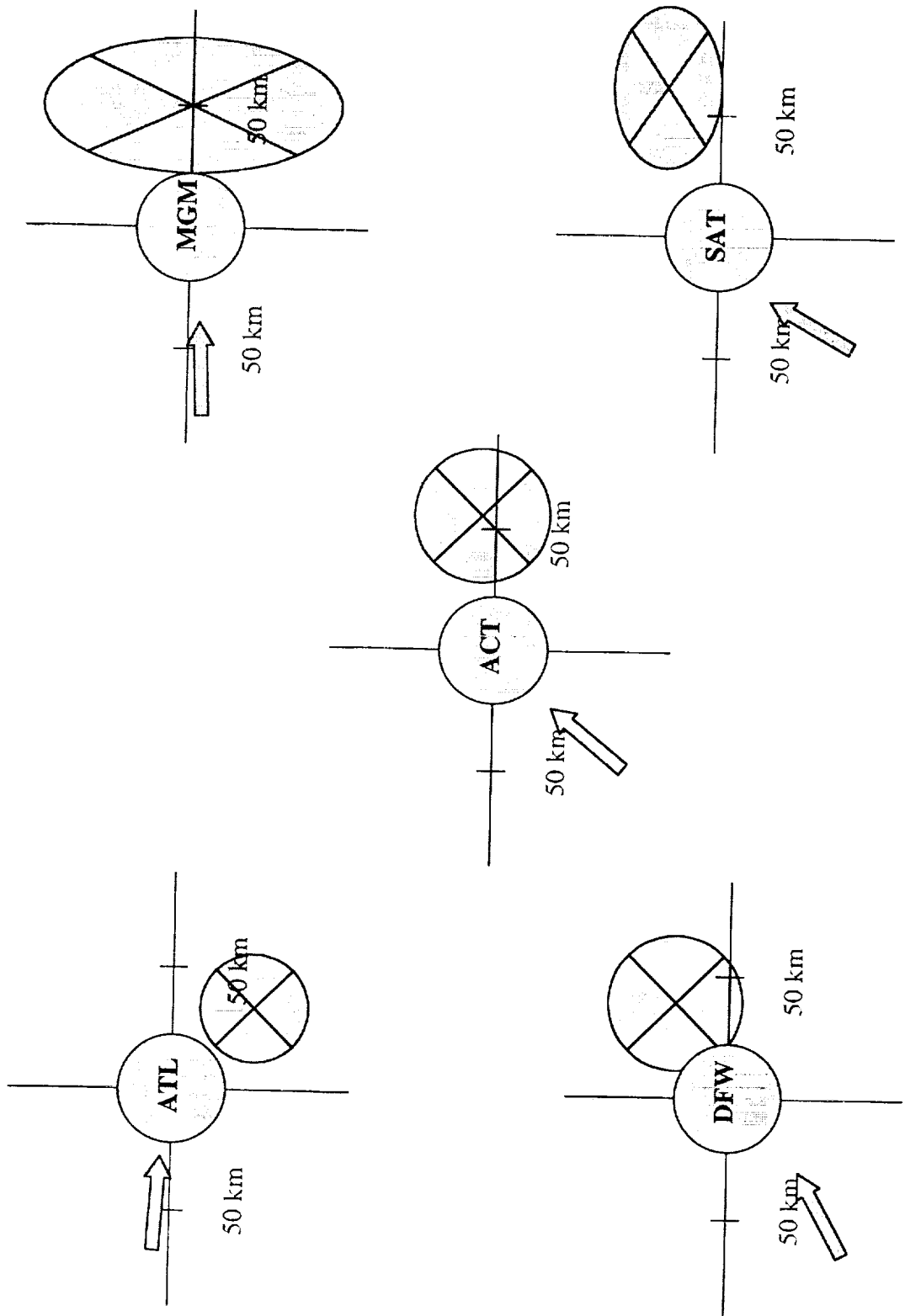


Fig. 13. Summary of the downwind locations for the cities experiencing the most significant urban-impacted rainfall (shaded cross region) in the warm season months. This analysis is based on the 3-year, warm season rainfall rate climatology provided by TRMM precipitation radar. The arrows represent the mean prevailing wind direction at 700 mb as determined by the NC AR/NCLEP reanalysis climatology (Kalnay et al. 1996).

City	Mean 700 mb Wind Direction (May to September)	Altitude (m)
Atlanta, Georgia	273 degrees	~320
Montgomery, Alabama	266 degrees	~190
Dallas, Texas	225 degrees	~140-230
Waco, Texas	210 degrees	~120-150
San Antonio, Texas	198 degrees	~100-15-

Table 1.0-Mean 700 mb Wind Direction (May to September) based on NCEP/NCAR Reanalysis geopotential height climatology from 1979 to 1998 (Kalnay et al. 1996). The approximate height above sea level (m) is also given.

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	Percentage Change in Urban Center Area from Upwind Control Area
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 2.0-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 Maximum 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 3.0-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.