A Reply to Diem et al.'s Commentary on A Recent Literature Contribution Focused on Urban-Induced Rainfall in Atlanta

Dr. J. Marshall Shepherd
Earth Science Directorate
NASA Goddard Space Flight Center
Greenbelt, Maryland 20771

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By Dr. J. Marshall Shepherd

Urban environments have been shown to impact a variety of weather and climate processes. Shepherd and colleagues recently published a paper in the literature demonstrating the feasibility of using the TRMM satellite's Precipitation Radar to identify rainfall anomalies associated with urban surfaces or aerosols.

Diem and colleagues, a group of geographers, published a note challenging the notion that TRMM data is appropriate or accurate for identifying urban rainfall anomalies. In the reply, we provide a point-by-point rebuttal of Diem and colleagues' comments illustrating the weaknesses in their arguments and their potential unfamiliarity with remote sensing techniques.

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Abstract

A response is provided to Diem and colleagues' discussion on the whether urbanization-enhanced precipitation should be maximized in the South-Southeast of Atlanta, Georgia as documented in Shepherd et al. (2003). Diem and colleagues have offered a critical response to Shepherd et al. (2002). The response herein offers both general and specific responses to issues raised by Diem and colleagues.

I. Introduction

The literature continues to indicate that the signature of the "urban heat island (UHI) 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). Rapid population growth in the last few decades has made Atlanta one of the fastest growing metropolitan areas in the United States. Because Atlanta is a model of rapid transition from forest/agriculture land-use to urbanization, NASA and other agencies have initiated programs such as the Atlanta Land-use Analysis: Temperature and Air Quality Project (ATLANTA) (Quattrochi et al. 1998).

2. Motivation and Previous Work

Such focus has led to a wealth of information on Atlanta's urban heat island (UHI) environment. Atlanta's UHI may also impact the global water cycle by inadvertent forcing of precipitating cloud systems. Bornstein and Lin (2000) used data from Project ATLANTA's 27 mesonet sites and eight National Weather Service sites to investigate interactions of the Atlanta UHI, its convergence zone, and convective storm initiation. Shepherd et al. (2002) recently found evidence that Atlanta and other urban areas may modify cloud and precipitation development. Dixon and Mote (2003) recently investigated the patterns and causes of Atlanta's UHI-initiated precipitation. Many results of recent studies are consistent with previous work. For example, early investigations (Changnon 1968; Landsberg 1970; Huff and Changnon 1972a) found evidence of warm seasonal rainfall increases of 9 to 17% over and downwind of major cities. The Metropolitan Meteorological Experiment (METROMEX) was an extensive study that took place in the 1970s in the United States (Changnon 1978; Huff 1986) to investigate modification of mesoscale and convective rainfall by major cities. In general, results from METROMEX have shown that urban effects lead to increased precipitation during the summer months. Increased precipitation was typically observed within and 50-75 km downwind of the city reflecting increases of 5%-25% over background values (Huff and Vogel 1978, Changnon 1979; Changnon et al. 1981; Changnon et al. 1991). More recent studies have continued to validate and extend the findings from pre-METROMEX and post-METROMEX investigations (Balling and Brazel 1987; Jauregui and Romales 1996; Bornstein and Lin 2000; Kusaka et al. 2000;

Thielen et al. 2000; Baik et al. 2001; Ohashi, and Kida 2002a; Changnon and Westcott 2002).

Diem and colleagues have offered a critical response to Shepherd et al. (2002). We are delighted that Shepherd et al. (2002) garnered the interest of our colleagues in the community and initiated a critical response. The response was well-posed and thought-provoking. The response that we offer stands by our initial findings; however, authors Diem and colleague raise some issues that we were keenly aware of. The response herein offers both general and specific responses to issues raised by Diem and colleagues.

II. General Comments In Repsonse to Diem and Colleagues

a. Intent of Shepherd et al. (2002)

Shepherd et al. (2002) was written with the intention of demonstrating the feasibility of the Tropical Rainfall Measuring Mission precipitation radar for identifying potential urban-induced rainfall signatures. As stated in section 3 of Shepherd et al. (2002), one of the novelties of the study was the application of satellite data to the problem of urban-induced precipitation. The authors always recognized that the TRMM dataset is not the optimal dataset for this type of study. In fact, we stated that TRMM is in a low-inclination orbit and is particularly suited and designed for capturing rainfall events at temporal scales of 1 month or greater. The study was not intended to utilize TRMM to identify:

a. Individual urban-induced storms

b. Seasonally-stratified events

c. Synoptic-regime events

These approaches are ideal but do not lend themselves to the 0.5 degree climate-focused datasets of TRMM. For this reason, we employed a more general approach in which climatological wind regimes (with variance around a mean vector) were correlated with climatological values offered by the TRMM data. For the more detailed approaches listed above, a more focused and appropriate dataset (gauges and ground-based radar are required). To this end, we are conducting the 2003-2004 Studies of PRecipitation Anomalies from Widespread urban Landuse (SPRAWL) field campaign. SPRAWL evolved because of our own skepticism in the satellite-results presented in Shepherd et al. (2002).

Shepherd et al. (2002) demonstrated that the University of Georgia Automated Environmental Monitoring Network (AEMN) (Hoogenboom, 1996) might not be sufficiently dense to capture the convective to meso-gamma scale rainfall anomalies associated with the urban heat island. This fact could be deleterious to any effort to identify convective scale precipitation anomalies in an urban area and lead to possible biases or gaps in the data. It is important in any spatio-temporal sampling to set the spacing between recorded samples at a maximum of half the wavelength of the spatial variation/periodicity of the process. Gridded TRMM Precipitation radar (PR) data used in Shepherd et al. (2002) are typically 0.5 degrees (~50 km) in spatial resolution. *This point illustrates the need for a higher density network (~25 km or less) near Atlanta to validate the TRMM satellite-indicated rainfall anomalies.*

NASA has deployed the NASA-Clark Atlanta University (CAU) Urban Rain Gauge Network (NCURN). NCURN is operated in conjunction with faculty and students at Clark Atlanta University and supplement AEMN and National Weather Service sites. The network consists of 25-30 gauges spaced at a resolution of approximately 25.0-km and centered on the geographic center of the Atlanta metropolitan area. Figure 1 is the emerging NCURN configuration. The NCURN was implemented as a long-term observation system and to support SPRAWL. The specific objectives of SPRAWL are:

- To conduct an intensive ground validation campaign of TRMM PR findings during the summer of 2003 (July-August) using the dense NCURN network in Atlanta and surrounding areas.
- To utilize ground and space-based datasets to identify and quantify "urban-induced" rainfall events over a 1-month period of intensive observation (IOP).
- To develop a "case study" validation dataset for comparison with simulations using the NASA Goddard Space Flight Center's version of the Mesoscale Modeling System (MM5) (Grell et al. 1994) coupled to the Parameterization for Land-Atmosphere-Cloud Exchange (PLACE) land surface model (Wetzel and Boone 1995)
- To develop a prototype continental-urban rainfall validation site for TRMM and future precipitation missions (e.g. Global Precipitation Measurement) to mitigate the problem of insufficient continental validation sites (Kummerow et al. 2000).
- To provide high spatial resolution, long-term rainfall monitoring capability around Atlanta.

SPRAWL is occurring during the summer of 2003 and 2004 in the Atlanta area in conjunction with NASA, National Weather Service, Clark Atlanta University, and the University of Georgia AEMN network. We have placed a dense rain gauge network around the city of Atlanta to fill gaps in the UGA AEMN network. During selected intensive operation periods (IOPS) we will collect rainfall, upper-level meteorological, and surface meteorological data. The purpose of this dataset is to establish a 2 year database of information that will allow us to address whether urban-induced rainfall occurs around Atlanta, what wind regimes are prevalent, what diurnal time period is preferred, and other relevant questions. *The author would emphasize here that SPRAWL was being planned as Shepherd et al. (2002) was being written because it was known and anticipated that the TRMM data could not be considered a conclusive dataset to thoroughly approach the urban rainfall problem.* Shepherd et al. (accepted with revisions to Journal of Atmospheric and Oceanic Technology) describes the NCURN network and SPRAWL

b. "Apples and Oranges"

Concerns about the accuracy of TRMM data may illustrate a possible unfamiliarity by Diem and colleagues with the space-based radar. Kummerow et al. (2000) reported that comparisons of PR-measured radar reflectivities with those measured by ground-based radar at NASA's Florida ground validation site show good agreements (differences within about 1 dB, on average). Schumacher and Houze (2000) compared the PR rainfall estimates with an S-band ground-based radar in Kwajelin Atoll and also found good agreement. They found that the PR only misses 2.3% of near surface rainfall relative to the ground-based radar and gauges. Similar calibration and validation studies corroborate these results (Bolen and Chandrasekar 2000, Heymsfield et al. 2000). The validation and calibration results indicate that the PR have been and will be sufficiently stable and accurate to assure quantitative rainfall estimates. In fact, operational agencies are considering the possibility of using the PR as a calibration constant to ground-based radars that are calibrated independently and rarely to the 1-dBZ standards of the PR (Kummerow et al. 2000).

We do not exhaustively discuss the accuracy of the TRMM radar in detail because the remote sensing community and those accustomed to the data generally accept that TRMM PR is an accurate system (within 1 dBZ of ground systems like the WSR-88D) and has a more rigorous calibration standard than most ground-based radars. Liao et al. (2001) provides more insight into calibration and validation of the TRMM PR. Therefore, we stand by the statement that "the PR has been sufficiently stable and accurate to assure quantitative rainfall estimates." Obviously, there will be errors associated with the Z-R conversion and assumptions but we do not feel that these errors are any more problematic than other rain-measuring systems.

Additionally, we emphasize that space-time-averaged PR data are utilized. The analysis was conducted on mean monthly "conditional" rainfall rates. Conditional rain rates account for events only where rainfall is detected in the grid box. Shepherd and Burian (2003) emphasized that because of the limitations of the TRMM conditional rain rate approach "TRMM PR rainfall rates are not the ideal dataset for detecting specific urban-induced events." Yet, it is important for Diem and colleagues to note that our data presents a "climatological snapshots of the mean "rainfall rates" in the study area when rain occurs. So essentially, our results show, for example, that when it does rain the rates tend to be higher in the SE quadrant of our area. We acknowledge that one of the biggest deficiencies with the Shepherd et al. (2002) study is that using conditional rainfall rates, we are likely working with a sample size in each grid box that is smaller than we would like and also location-variant. We address this to some degree in the approaches of Shepherd and Burian (2003) but recognize this approach as a limitation. As a reminder, when we reported these results we were somewhat skeptical also. For this reason, we planned and are conducting the SPRAWL campaign.

In many of the analyses presented in Diem et al., the authors display monthly rainfall amounts. This is an "apples and oranges comparison" to the "conditional rainfall rates" of Shepherd et al. (2002). We state this fact in the paper. In fact, what our results really say is that urban-induced rainfall is generally convective in nature and has preferred regions. Comments in section III further address some of these issues.

III. Response to Specific Comments by Diem et al.

a. Diurnal Bias

We disagree with the assertion that our data is biased. 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. Because of the nature of the TRMM "conditional rain rates", it is true the values for a given grid box may be contributed from an array of systems and diurnal times. The authors are aware of the nice work by Dixon and Mote (2003) but have some fundamental disagreement with some of their findings. Typically the peak in urban-rural surface temperature difference is in the late evening time window, as stated by Diem et al. However, the urban heat island circulation, boundary layer destabilization and associated low-level convergence (e.g. all of which are more important for convective development than simple surface UHI surface temperature gradient) are most evident during the daytime. This fact is due to the greater urban-rural pressure gradient and vertical mixing during daytime hours (Sheffler,1978,; Fujibe and Asai 1980, Kusaka et al. 2000, Ohashi and Kida, 2002). Recent modeling results at using a mesoscale model supports these findings that dynamic, daytime dynamic forcing is the dominant forcing mechanism for the UHI-rainfall. During the summer, moisture is generally sufficient in Atlanta so the authors are not convinced that moisture is the "smoking gun" as Dixon and Mote (2003) seems to suggest.

Furthermore, we would hypothesize that Dixon and Mote's (2003) decision to exclude widespread "daytime" heating convection from their database may represent a deficiency. These storms are likely characteristic of what would be considered "urban-heat" island generated storms since we know that "daytime heating" thunderstorms are likely forced by something other than simply "daytime heating" (e.g. UHI convergence, outflow boundaries, etc.). In general, Dixon and Mote's (2003) criteria may be too restrictive and thereby bias the diurnal tendency of UHI-induced convection.

b. Mesoscale or Not?

Diem and colleagues state that at scales of roughly 50 km, it is impossible to conduct comparisons within a mesoscale context. On one hand, we would love to have finer resolution data (hence SPRAWL) but our intent was to demonstrate the ability for TRMM 0.5 degree PR data to identify mesoscale signatures. In fact, the study was motivated by analyses of the 0.5 degree data that continued to illustrate clearly-defined rainfall signatures associated with sea breeze fronts and orography, both of which are mesoscale forcing mechanisms. It is also worth reminding Diem and colleagues that the mesoscale spans from meso-gamma (~ 2 km) to meso-alpha (~2000km) based on Orlanski (1975). Other definitions presented in Mesocale Meteorology and Forecasting (edited by Peter Ray, 1986) are also consistent with Orlanski (1975).

c. Tropical System Bias

The discussion of whether tropical systems biased our data is valid. We were generally concerned also that our data might be biased by tropical activity although our preliminary analysis couldn't justify why the tropical contribution would be so concentrated in the SE quadrant when most of the systems during this period produced fairly widespread rainfall over the entire Atlanta area.. However, this uncertainty is another reason why we are conducting the SPRAWL campaign.

d. Ecological Fallacy

Shepherd et al. (2003) chose to plot contours of the 0.5 degree data for presentation clarity but recognized that the Barnes-type analysis utilized in GEMPAK may have overly smooth the data. In Shepherd and Burian (2003), we have chosen to plot the data in grid boxes of native resolution (Figure 2). Had we done this in Shepherd et al. (2002), a distinct anomalously high region was still evident in the SE of the metropolitan area. We acknowledge that the objective analysis treatment presented in Shepherd et al. (2002) was probably not the optimal treatment. We were not trying to "downscale", we simply wanted a cleaner presentation using contouring.

e. Ensemble Averaging

As stated previously, we did not intend to try to stratify synoptic regimes or individual cases because the satellite's climate-centric dataset did not lend itself to this more detail (and preferred) analysis. To investigate the capabilities of satellite-based measurements for identifying urban effects on rainfall, a working hypothesis was established, similar in philosophy to Huff and Changnon (1972a). In their framework, hypothesized areas of urban effect and no-effect on a climatological time scale were determined. Their study 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.

- 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° 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.

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). 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. For each city, the HRA is oriented according to the mean prevailing wind direction. The 125° sector accounts for the "steering" directions representing means that include values greater or less than the mean value; therefore, the mean impacted area accounts for the spread of values that encompass the mean (e.g. the deviation). We are still comfortable with this approach for the TRMM dataset but recognize it as limited. SPRAWL will allow for more robust stratification based on case-by-case wind regimes and system classification (e.g., frontal, weak forcing, etc.).

At this point, we re-emphasize that Diem et al should not misconstrue that this study was meant to be a "robust" analysis of Atlanta's urban induced rainfall tendencies. Instead, it was trying to establish that a unique space-rain radar was detecting rainfall rate signatures that might be linked to urban-induced rainfall. This study offered a preliminary assessment for the more in-depth field and modeling work that SPRAWL will enable.

f. Rainfall Map Comparisons

The map that we presented on amount was used as a qualitative tool to illustrate broadly the rainfall distribution. We stand by the accuracy of our analysis. Furthermore, Shepherd et al. (2002) did not go into a detailed analysis because its "apples and oranges," and there is no way to provide a meaningful comparison between gauge-amounts and TRMM "conditional rainfall rates" (conditional rainfall rates previously defined).

g. Topography

The author is from Cherokee County, GA and is very familiar with the topography in Georgia. In fact, we state that ATL area is "relatively" flat. This was in comparison with cities like Phoenix or Denver that have substantial surrounding relief (defined as > 500 m above sea level). In fact, Shepherd et al. (2002) acknowledged that the Atlanta area was not flat by listing its altitude in Table 1 of that paper. However, we emphasize that we do not believe that the relief is a primary factor in this study. Substantial evidence of topography-induced signatures in the mountainous South Carolina, North Carolina, and Georgia regions were observed when we examined annual data from TRMM.

h. Distance

Diem et al. are correct in noting that gauging a downwind distance is not possible from this dataset. For this reason, we chose to give a distance range. Guided by our recent model results and SPRAWL results, we hope to quantify a distance with more conclusiveness in the future.

IV. Conclusions

Diem and colleagues have encouraged the authors by expressing a keen interest in Shepherd et al. (2002). Recent work by this author and several colleagues in the community continue to show evidence that urban areas are causing discernible anomalies in precipitation. Diem and colleagues raise some valid issues in their paper, but most of them do not ultimately negate the value and intent of Shepherd et al. (2002). Their comments suggests that they did not fully understand the intent of Shepherd et al. (2002) was to offer a new "prototype" approach for studying urban rainfall anomalies. Recent urban sessions at the 2003 Fall American Geophysical Union meeting and the 2004 American Meteorological Society Annual meeting illustrate the renewed interest in the subject matter. Our approach in Shepherd et al. (2003) used a satellite-based technique to study the problem but never intended to suggests that its results were conclusive or thoroughly studied. Instead, the goal was to stimulate new ground-based efforts like SPRAWL, additional satellite observations, and modeling studies. Over the next decade, more research will be required to firmly answer questions that have arisen over the last few decades concerning urbanization and precipitation variability.

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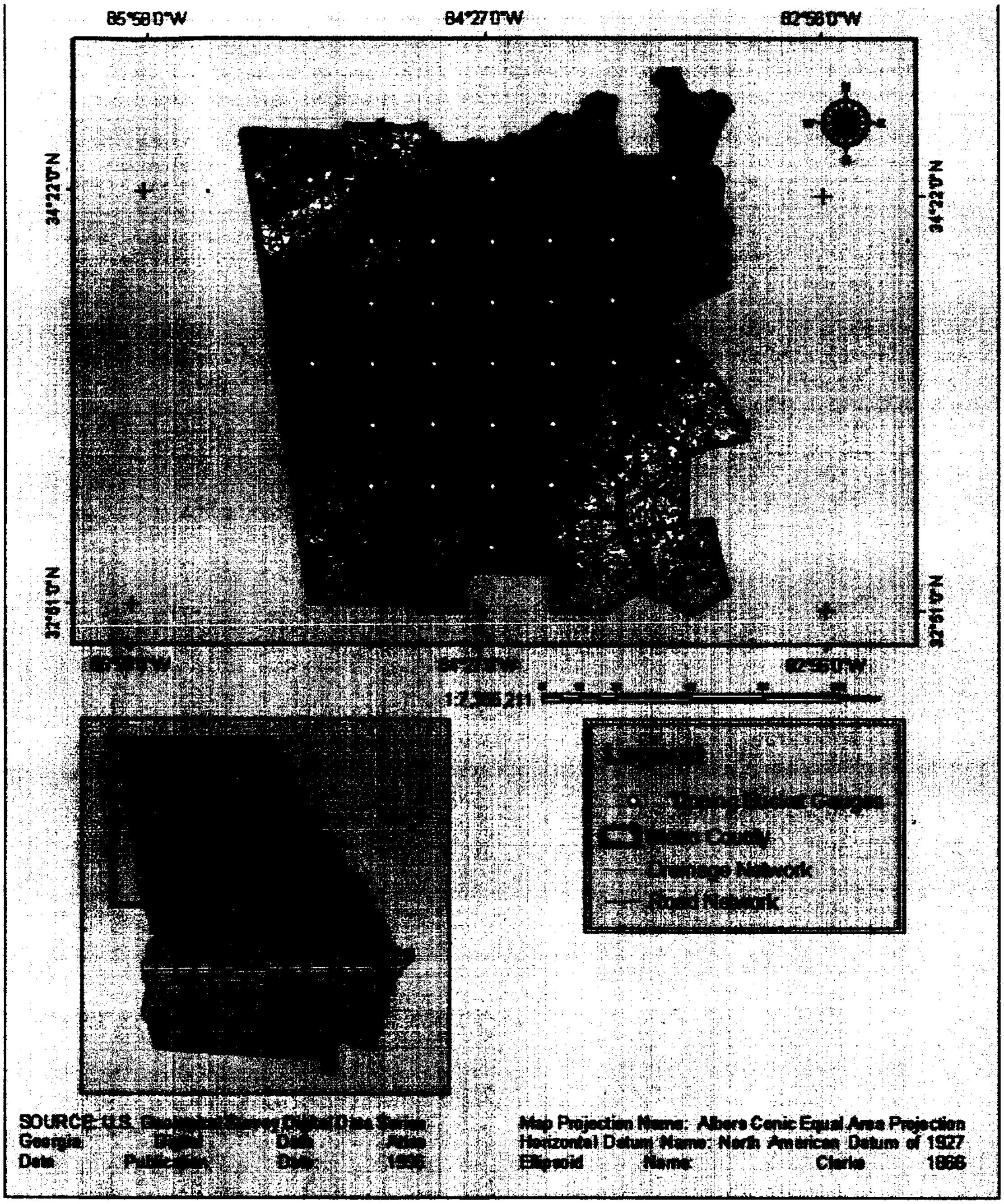
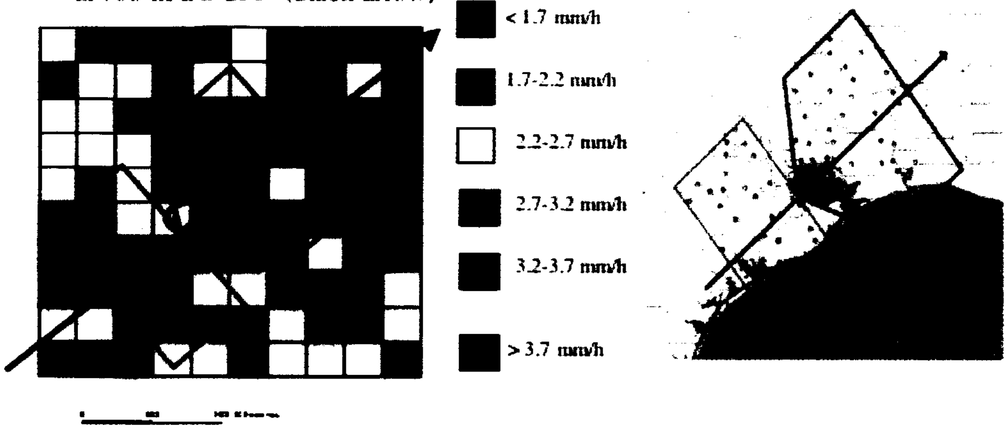

85°58'0"W
84°27'0"W
82°58'0"W
34°22'0"N
32°51'0"N
Map Projection Name: Albers Conic Equal Area Projection
Horizontal Datum Name: North American Datum of 1927
Ellipsoid Name: Clarke 1866

Figure 1

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



TRMM PR at 0.5 Degree
with Coordinate System

Houston Area with
Coordinate System and
Gauge Locations

Figure 2