1.6 Status of NASA Satellite, Field Observations, and Numerical Modeling Addressing the Impact of Urbanization on Short and Long Term Precipitation Variability

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1.0 Introduction

Howard (1833a) made the first documented observation of a temperature difference between an urban area and its rural environment. Manley (1958) termed this contrast the "urban heat island (UHI)". The UHI has now become a widely acknowledged, observed, and researched phenomenon because of its broad implications. It is estimated that by the year 2025, 60% of the world's population will live in cities (UNFP, 1999). In the United States, the current urban growth rate is approximately 12.5%, with 80% currently living in urban areas. As cities continue to grow, urban sprawl creates unique problems related to land use, transportation, agriculture, housing, pollution, and development for policymakers. Urban expansion and its associated urban heat islands also have measurable impacts on weather and climate processes (figure 1).

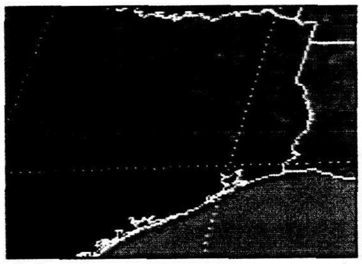

Figure 1-3.9 micron channel image of urban heat islands (darker regions) in Texas.

To further understand the origins of the UHI, it is instructive to examine a surface heat budget equation,

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

In equation (1), the terms are net short-wave irradiance (Q_{SW}), net long-wave irradiance (Q_{LW}), surface sensible heat flux (Q_{SH}), latent turbulent heat flux (Q_{LE}), anthropogenic heat input (Q_A), and ground heat conduction (Q_G). 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. For the UHI, the difference in surface properties of urban and rural areas leads to the differences in thermal fluxes in (1).

Precipitation is a key link in the global water cycle and a proper understanding of its temporal and spatial character will have broad implications in ongoing climate diagnostics and prediction, Global Water and Energy Cycle (GWEC) analysis and modeling, weather forecasting, freshwater resource management, and land-atmosphere-ocean interface processes (Figure 2).

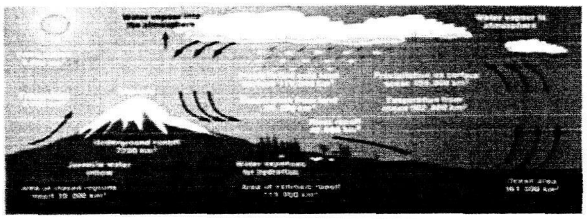

Figure 2-Earth's water cycle.

2. Previous and Current UHI-Precipitation Linkages

A recent U.S. Weather Research Program panel concluded that more observational and modeling research is needed on urban induced-rainfall (Dabberdt et al. 2000). First, previous research used ground observations to study one or few selected cities. However, urban effects vary with the micro- to mesoscale features of individual cities. Globally assessment of urban climate over long periods of time is necessary to generalize the most important characteristics of urban effects. Second, previous studies, via different approaches, reached conflicting understanding on urban-rainfall relations. It is reported that urban areas reduce rainfall due to cloud microphysics (Rosenfeld 1999; Ramanathan et al. 2001), yet historical (METROMEX work) and more recent studies showed that urban areas enhance rainfall over and downwind of cities (Shepherd et al. 2002, Changnon and Westcott 2002, Ohashi and Kida 2002a). Using the Tropical Rainfall Measuring Mission's (TRMM) Precipitation Radar (PR) and a limited network of irregularly spaced, ground-based rain gauges, Shepherd et al. (2002) and Shepherd and Burian (2003) recently found evidence that Atlanta, Houston and other urban areas may modify cloud and precipitation development in downwind regions by 14.6 to 51%.

They speculated that the change was linked to heavy urban development in what is now the fourth largest U.S. city, covering an area of 937 km^2. Orville et al. (2001) analyzed 12-years (1989-2000) of ground-based

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lightning data for the Houston area. They found that the highest annual and summer flash densities were over and downwind (e.g., Northeast-East) of the Houston area. Using mesoscale model simulations, they hypothesized that the lightning distribution was caused by either a combination of urban heat island-induced convergence or enhanced lightning efficiency by increased urban aerosols. Since lightning is a signature of convection in the atmosphere, it would seem reasonable that urbanized Houston would also impact the distribution of rainfall. Shepherd and Burian (2003), using data from TRMM and ground-based rain gauges, have identified rainfall anomalies over and downwind of Houston that are consistent with Orville et al. (2001)'s findings (figure 3).

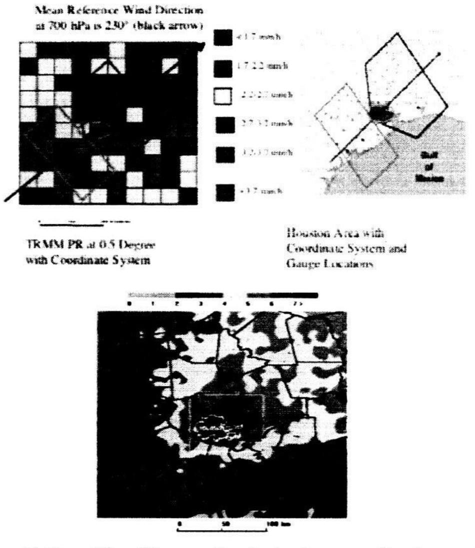

Figure 3-Top-The "theoretical study coordinate system" with mean annual distribution of TRMM-derived rainfall rates from January 1998 to May 2002 (excluding August 2001). The orange oval is the approximate Houston Urban Zone and is centered on (29.75, 95.75) and (29.75, 95.25), respectively. The black vector represents the mean annual 700 hPa steering direction. The pentagon-shaped box is the "downwind urban impacted region (DUIR)" and the rectangular box is the "upwind control region (UCR)". Bottom-Mean Annual Flash Densities (per square kilometer per day): Highest Flash Densities (> 4 square kilometers) are over and just downwind of the Houston Urban area (following Orville et al. 2001).

We also include various results from Burian et al. (2003) illustrating results from gauge analyses. Figure 4 is an analysis that illustrates a shift upward in percent rainfall in a pre-urban to post-urban period for a gauge in the urban downwind part of Houston; whereas, a gauge in the upwind region remained essentially unchanged. Figure 5 illustrates that warm season rainfall in the upwind, urban, and downwind (urban impacted) regions have distinct diurnal trends. We hypothesize that urban processes impact the late afternoon maxima in the urban-impacted region. Part of this pattern is explained by the diurnal activity associated with the sea-breeze front. However we hypothesize that the downwind region experiences additional "convective forcing" because of urban-induced convergence and destabilization. Current modeling efforts seek to test these hypotheses. Shepherd et al. (2002), Shepherd and Burian (2003), and Burian et al. (2003) findings 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 the1970s in the United States (Changnon 1978; Huff 1986) to further investigate modification of mesoscale and convective rainfall by major cities. In general, results from METROMEX have shown that urban effects lead to increased precipitation during the summer months. Increased precipitation was typically observed within and 50-75 km downwind of the city reflecting increases of 5%-25% over background values (Huff and Vogel 1978, Changnon 1979; Changnon et al. 1981; Changnon et al. 1991). More recent studies have continued to validate and extend the findings from pre-METROMEX and post-METROMEX investigations (Balling and Brazel 1987; Jauregui and Romales 1996; Bornstein and Lin 2000; Kusaka et al. 2000; Thielen et al. 2000; Baik et al. 2001; Ohashi, and Kida 2002a; Changnon and Westcott 2002).

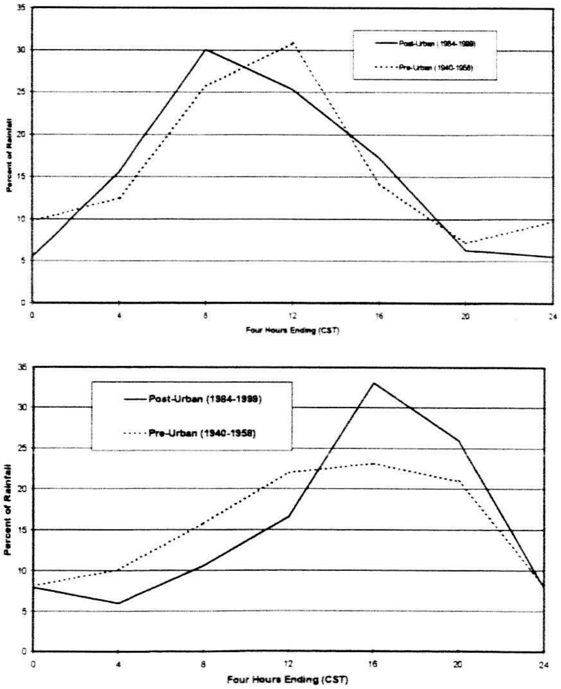

Figure 4-Top-Analysis of percent of rainfall at Gauge 3430H in the Upwind region of Houston during pre-urban (1940-1958) and post-urban (1984-1999) periods. Bottom-Analysis of percent of rainfall at Gauge 4311H in

the Downwind region of Houston during pre-urban and post-urban period (from Burian et al. 2003).

NASA and other agencies initiated programs such as the Atlanta Land-use Analysis: Temperature and Air Quality Project (ATLANTA) (Quattrochi et al. 1998) which aim to identify and understand how urban heat islands impact the environment. However, a comprehensive assessment of the role of urban-induced rainfall in the global water and energy cycle (GWEC) and cycling of freshwater is not a primary focus of these efforts. NASA's Earth Science Enterprise (ESE) seeks to develop a scientific understanding of the Earth system and its response to natural or human-induced changes to enable improved prediction capability for climate, weather, and natural hazards (NASA, 2000). Within this mission, the ESE has three basic thrusts: science research to increase Earth system knowledge; an applications program to transfer science knowledge to practical use in society; and a technology program to enable new, better, and cheaper capabilities for observing the earth. Within this framework, a comprehensive program was recently funded by NASA's ESE to further address the co-relationship between land cover use and change (e.g. urban development) and its impact on key components of the GWEC (e.g., precipitation). Herein, key components of the program are outlined.

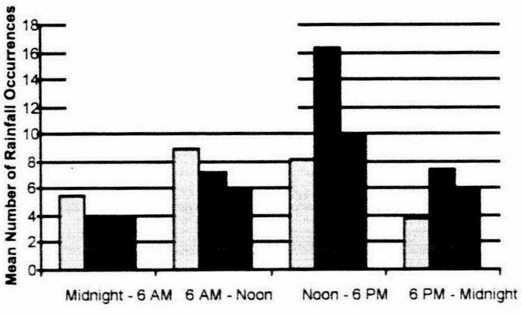

Figure 5-Diurnal trends, in terms of mean fraction of daily rainfall, for upwind (yellow), urban (red), and downwind (blue-UIR) gauges.

3. Overall Objectives and Research Strategy

The urban influence on rainfall is likely caused by one or a combination of factors: (1) Enhanced thermal mixing due to Urban Heat Island (UHI) boundary layer destabilization; (2) Increased turbulence and mechanical mixing (leading to enhanced convergence) due to increased aerodynamic roughness created by tall buildings, (3) Modified low-level atmospheric moisture, potentially caused by augmented water and energy budgets; or (4) Increased concentrations of cloud condensation nuclei (CCN) from automobiles and industry.

The objectives of the research are:

- To analyze satellite and ground-based rainfall data to identify rainfall anomalies associated with Atlanta, Houston, and other cities in the United States (U.S.) and elsewhere. This objective will delineate rainfall anomalies linked to urbanization, and enable assessment of global cities rather than specific cities.
- To conduct modeling studies of urban-induced precipitation using improved urban land surface parameterizations linked to a mesoscale model.
- To conduct field experiments to validate satellite findings and better understand the physical processes linking urban land use to precipitation variability .
- To detect weather and climate signals (precipitation -related) that may be linked to urbanization.

4. Studies of Precipitation Anomalies from Widespread urban Landuse (SPRAWL)

Rapid population growth in the last few decades has made Atlanta one of the fastest growing metropolitan areas in the United States. The population of the Atlanta metropolitan area increased 27% between 1970 and 1980, and 33% between 1980-1990 (Research Atlanta, Inc. 1993). From 1973 to 1992, the Atlanta area experienced a decline of nearly 20% in forestland. LANDSAT 5 data illustrate the rapid growth of urban surfaces in Atlanta. 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). Project ATLANTA was a multi-disciplinary effort to study the UHI.

Such focus led to a wealth of information on Atlanta's 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 show that the UHI could induce a convergence zone that could initiate convection. However, a focused assessment of the role of urban-induced rainfall in Atlanta has not been a primary focus of past efforts.

i. NASA Clark Atlanta Urban Rain Gauge Network

NASA developed the NASA-Clark Atlanta University (CAU) Urban Rain Gauge Network (NCURN). NCURN will be operated with Clark Atlanta University and supplement AEMN and National Weather Service sites (Shepherd et al. 2003). 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 6 is the theoretical NCURN configuration. The NCURN was implemented as a long-term observation system and to support the 2003 **Study of Precipitation Anomalies from Widespread urban Landuse (SPRAWL)** experiment SPRAWL is a NASA-funded experiment:

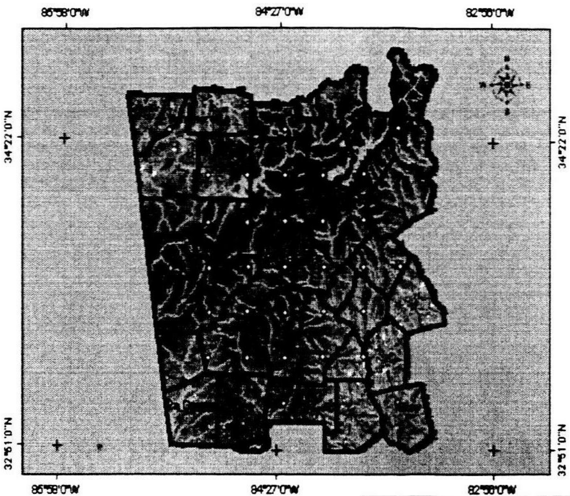

Figure 6-NCURN rain gauge network framework.

- To conduct an intensive ground validation campaign TRMM PR findings during the summer of 2003 (July-August) using the dense NCURN network in Atlanta and surrounding areas.

- To utilize diverse datasets (e.g. TRMM, NCURN, AEMN, and WSR-88D) 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 version of the Mesoscale Modeling System (MM5) (Grell et al. 1994) coupled to the Parameterizaton-Land-Atmosphere-Cloud Exchange (PLACE) land surface model (Wetzel and Boone 1995). MM5-PI case studies will improve understanding of physical dynamical processes that lead to urban-induced circulations. A new urban land parameterization is currently being implemented into PLACE to more accurately resolve critical urban parameters like roughness length, skin temperature, albedo, leaf-area index, and vegetative fraction. This parameterization based on MODIS and airborne LIDAR-derived parameters. Preliminary results of a simulation of a Houston July case day using MM5-OSU land surface model and MM5-PLACE land surface model are presented in figure 7. The Houston UHI is clearly evident in the ground temperatures (dark reds west of Galveston bay).

- 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.

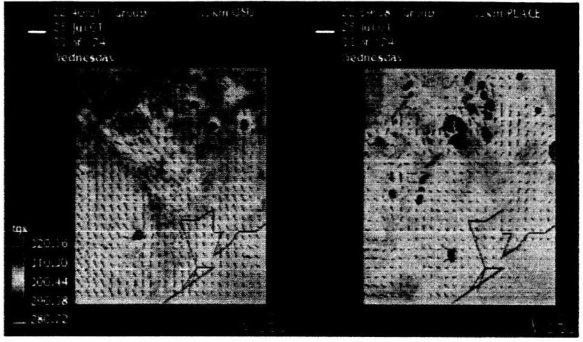

Figure 7-Preliminary MM5-OSU (left) and MM5-PLACE simulations for a July 25-26 case day in Houston. Warm and cool colors represent ground temperature. Green colors represent precipitation. Black vectors represent wind at 300 meters above the surface.

Summary

There is renewed interest in the impacts of urbanization on global change as witnessed by special sessions at the Fall AGU and Annual AMS meeting. A comprehensive satellite, modeling, and field campaign program is underway to assess the impact of urbanization on precipitation.

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