JP5.1 THE IMPACT OF URBANIZATION ON THE PRECIPITATION COMPONENT OF THE WATER CYCLE: A NEW PERSPECTIVE

J. Marshall Shepherd, NASA/GSFC, Earth Sciences Directorate, Greenbelt, Maryland

1. 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. The U.S. population is not only growing but is tending to concentrate more in urban areas in coastal zones (Culliton et al. 1990). 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. The UHI has been documented in the literature to affect local and regional temperature distributions (Hafner and Kidder 1999), wind patterns (Hjemfelt, 1982), and air quality (Bornstein and Lin, 1999). The UHI may also impact the global water cycle through development of clouds and precipitation in and around cities.

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 enhanced low level heating; 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. 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). 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. 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. *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.*

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) 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 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 (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; Thielen et al. 2000; and Baik et al. 2001). However, a recent U.S. Weather Research Panel report (Dabberdt et al. 2000) indicated that more observational and modeling work is required because previous results were heavily based on a few specific cities and statistical inferences. Figure 1 highlights some recent findings (Shepherd et al. 2002) using Tropical Rainfall Measuring Mission (TRMM)

Corresponding Author: Dr. J. Marshall Shepherd, NASA/GSFC, Code 912.0, Greenbelt, MD 20771, email: shepherd@agnes.gsfc.nasa.gov

precipitation radar data to identify and quantify hypothesized rainfall anomalies caused by cities like Dallas and Atlanta.

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.

2. OBJECTIVES AND RESEARCH STRATEGY

The ESE's Research Strategy is based on a hierarchy of scientific questions seeking to answer the question "How is the Earth changing and what are the consequences for life on Earth." This broader question is decomposed into five guiding questions:

- How is the global Earth system changing?
- What are the primary forcings of the Earth system?
- How does the Earth system respond to natural and induced changes?
- What are the consequences of change in the Earth system for human civilization?
- How well can we predict future changes in the Earth system?

This work seeks to investigate the phenomenon of urban-induced precipitation anomalies using satellite-based remote sensing and numerical modeling techniques. This broad objective offers real possibilities for improving our understanding of how the GWEC responds to land cover use and change (LCUC), what the implications of inadequate representation of urban surfaces in mesoscale forecast models are, and what potential new societal benefits can be derived from this knowledge. A third tier of questions is decomposed from the five aforementioned ESE strategy questions and provides a set of questions that refine and delimit the components of and processes within the Earth system of particular interest to the ESE. The proposed work is aligned very closely with the following key questions:

a. *How are global precipitation, evaporation, and the cycling of water changing? (Variability)*
b. *What changes are occurring in global land cover and land use, and what are the causes? (Forcing)*
c. *How is the Earth's surface being transformed and how can such information be used to predict future changes? (Forcing)*
d. *What are the effects of clouds and surface hydrologic processes on Earth's climate? (Response)*
e. *How are variations in local weather, precipitation, and water resources related to global climate variation? (Consequences)*
f. *What are the consequences of land cover and land use change for the sustainability of ecosystems and economic productivity? (Consequences)*
g. *How can weather forecast duration and reliability be improved by new space-based observations, data assimilation, and modeling? (Prediction)*

The objectives of the research are:

1. To analyze past, current, and future TRMM Radar (PR) data to identify rainfall anomalies associated with urban areas in the United States (U.S.) and elsewhere. This objective will extend recent work by Shepherd et al. (2002), further validate space-based platforms' ability to delineate rainfall anomalies linked to urbanization, and enable assessment of global cities rather than specific cities.

Shepherd et al. (2002) established that TRMM and future space-based radar systems (e.g. GPM's dual frequency radar) can detect UHI-induced rainfall anomalies. This fact is important because much of the uncertainty about UHI-rainfall comes from the limited sample of studies conducted for specific cities in field campaigns. Space-based observations enable global assessment of UHI-induced rainfall over longer periods of time thereby allowing for analysis of cities around the world.

We extend and expand the analysis of Shepherd et al. (2002) to additional cities in the United States and internationally by:

- Integrating additional years of TRMM PR data thereby utilizing a more robust sample of data (see section 4.b.1) for previously studied cities (e.g. Dallas, Atlanta, Austin, Montgomery, Waco). *This proposed action could extend Shepherd et al. (2002) from a 3-year dataset to a 6-7 year dataset (e.g. a climatology).*

- Extending analysis in bullet item #1 to Phoenix, Arizona which Balling and Brazel (1987) and Selover (1997) identify as a city that experiences rainfall modification due to rapid urbanization. Phoenix is an urban area with serious water management and rainfall issues. *This proposed action would serve as a focused case study on the feedback between land use change and its potential impact on the water cycle.*

- Expanding the methodology to examine international cities that have (1) been identified in the literature as cities that experience UHI-induced rainfall or (2) meet criteria for selecting cities in section 4.b.1. The cities that have been selected include Mexico City, Mexico, Johannesburg, South Africa, Brasilia, Brazil, and Chongqing, China. Five to ten additional cities may be investigated if time and resources are available. *This proposed action would demonstrate the utility of global analysis of UHI-induced rainfall anomalies using satellite-based rainfall estimates.*

Early new research is already bearing fruitful knowledge. For example, There is increasing evidence that large coastal cities, like Houston, Texas, can influence weather through complex urban land use-weather-climate feedbacks. A hydrologic-engineering study by Bouvette et al. (1982) presented statistical evidence from 4 Houston area rainfall-recording stations that the 24-hr 100-yr storm depth had increased by 15% in suburban areas when compared to the 24-hr 100-yr storm depth published in 1961 by the National Weather Service. 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 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 (Figure 1a). Using mesoscale model simulations (figure 1b), 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. Early analysis of data from the TRMM and ground-based rain gauges have identified rainfall anomalies over and downwind of Houston that are consistent with Orville et al. (1991)'s findings (figure 2). It is one of the first rigorous efforts to quantify an urban-induced rainfall anomaly near a major U.S. coastal city and one of the first applications of space-borne radar data to the problem (Shepherd and Burian 2003).

2. To conduct an intensive ground validation campaign of TRMM PR findings from objective (a.) during summer of FY03 using a super-dense urban rain gauge network in Atlanta, Georgia and surrounding areas. This objective allows for consistent validation of satellite results and development of "prototype" TRMM/Global Precipitation Measurement (GPM) validation products for an Urban-Continental environment,

We plan to conduct an intensive ground validation campaign in the Atlanta, Georgia metropolitan area during the summer of 2003. This component of the proposal is critical because it: (1) establishes ground-validation of TRMM PR rainfall estimates at one of the urban areas examined Shepherd et al. (2002), (2) provides for the development of "pilot" ground validation products at an urban continental site, and (3) establishes a fairly dense rainfall observation network in an urban environment.

Rapid population growth in the last few decades has made Atlanta one of the fastest growing metropolitan areas in the United States. From 1973 to 1992, the Atlanta area experienced a decline of nearly 20% in forestland. 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 Urban Heat Island Experiment (1997) and the Atlanta Land-use Analysis: Temperature and Air Quality Project (ATLANTA) (Quattrochi et al. 1998). Such programs aim to identify and understand how UHIs impact the environment in terms of land use, air quality, health, climate, and other factors. Such focus has led to a wealth of information on Atlanta's urban heat island environment. Additionally, a fairly robust rain gauge network, the Georgia Automated Environmental Monitoring Network (AEMN) (Hoogenboom, 1996), exists in the Atlanta area along with National Weather Service assets.

Shepherd et al. (2002) demonstrated, however, that the AEMN might not be sufficiently dense to capture the convective to meso-gamma scale rainfall anomalies associated with the urban heat island. Additionally, many of the gauges in the AEMN are not tipping-bucket systems required for rainfall rates similar to those calculated from the TRMM PR. A close examination of Fig. 3 (red dots) reveals that areas (particularly southeastern sections) of metropolitan Atlanta are poorly sampled by the AEMN network thereby leading to possible biases in the data. This point illustrates the need for higher density networks near cities to validate the satellite estimates.

We propose to supplement the AEMN with a nested set of tipping bucket rain gauges. The so-called NASA-Clark Atlanta University (CAU) Urban Rain Gauge Network (NCURN) will be operated in conjunction with faculty and students at Clark Atlanta University. The network will consist of 25 gauges spaced at a resolution of approximately 25.0-km and centered on the geographic center of the Atlanta metropolitan area (fig. 3). This configuration allows for coordinated comparison with the 0.5°-latitude TRMM PR gridded data.

After the NCURN is in place, the investigators in partnership with students at Clark Atlanta University will archive hourly measurements of rainfall data during the period May-September 2003 for comparison with TRMM PR data over the same period. To facilitate a meaningful comparison, we will develop a set of rainfall products consistent with the TRMM PR and NCURN gauge measurements. Both TRMM and NCURN-gauge products will be objectively analyzed to a standard Cartesian reference grid. The three standard products that will be analyzed are: Mean monthly rainfall rate (mm/day), Total monthly rainfall (mm), and Total Days with Measurable Rain

These products (along with others as proposed by the PI) will serve as the deliverable products of the NCURN. Additionally, they provide a unique ground validation data set in a continental urban environment. This is important because the primary focus of TRMM validation efforts have been in the deep tropics and near coastal interfaces. Kummerow et al (2000) remarked that more detailed TRMM validation over land is required to fully understand algorithm results in different climatological regimes. Furthermore, as Global Precipitation Measurement (GPM) evolves, more non-tropical, continental validation sites will be required. We propose the NCURN site as representative of an urban, continental climate regime and as a potentially continuous observing network.

3. To integrate urban land parameterizations into a coupled cloud-mesoscale-land surface model to conduct experiments to investigate physical-dynamical links between urban land use, the evolution of atmospheric circulations, and resulting precipitation fields. This objective will also provide guidance into whether emerging mesoscale forecast models must consider urbanization explicitly in land surface parameterizations.

i. Cloud-Resolving Model and Land Surface Model Simulations

The final scientific component of the study employs the Goddard Cumulus Ensemble (GCE) model (Tao and Simpson 1993) and the Goddard-version of MM5 mesoscale model (Grell et al. 1994). Both models will be coupled to the Parameterization for Land-Atmosphere-Cloud Exchange (PLACE) land surface model (Wetzel and Boone 1995) to investigate the impact of urban land characteristics and associated fluxes on the physical-dynamical processes leading to UHI-induced precipitation anomalies.

Previous studies have identified the importance of the lower surface boundary condition for cloud and mesoscale models for some time (Pielke et al. 1991). Detailed representation of heat and moisture transfer between surface and atmosphere has only recently been included in cloud-mesoscale modeling (Lynn et al. 1998; Thielen et al. 2000; Baik et al. 2001; Baker et al. 2001). The difficulty with such applications has been that heat and moisture transfers at the surface depend on a variety of soil and vegetation parameters and realistic treatment of the lower boundary requires these parameters. Additionally, many soil models or coupled land surface-atmospheric models are only *designated for rural surfaces and not urban surfaces* (Thielen et al. 2000). We propose to integrate parameterizations characteristic of urban surfaces (e.g. concrete, asphalt, stone, slate) into GCE-PLACE and MM5-PLACE to understand how an urban land interface and associated heat and moisture fluxes impact the evolution of atmospheric circulations and the water cycle (e.g. precipitation).

The GCE model has been extensively applied to *explicitly* resolving cloud-environment interactions, cloud development, and evolution of cloud-mesoscale precipitating systems. The model includes solar and infrared radiative processes and explicit cloud microphysics incorporating liquid and frozen hydrometeor species. The model also includes extensive parameterization of subgrid-scale (turbulent) processes. GCE-PLACE is described in Lynn et al. (1998) and Baker et al. (2001). This version of the GCE model has been modified to include the land surface part of the PLACE model. PLACE provides state-of-the-art representation of land surface processes. The boundary conditions are obtained from an energy balance equation at the surface. The momentum, sensible, and latent heat fluxes are calculated using similarity relationships described in Lynn et al. (1998). The soil component of the land surface model has up to seven model layers, five for soil moisture and seven for temperature. At the soil surface, soil water infiltration processes are included following Wetzel and Boone (1996), while the flux of heat into the soil is dependent upon a thermal conductivity (McCumber and Pielke 1981). Soil moisture is also interactive and includes evaporative processes, rainfall, runoff, and drainage. The vegetation component of the model is represented as a single layer that accounts for vegetation type, leaf area index, fractional vegetation cover, and other variables.

Herein, the three-dimensional version of GCE-PLACE will be employed to (1) determine if a UHI thermal perturbation can induce a dynamic response to initiate rainfall processes and (2) quantify the impact of the following factors on the evolution of rainfall: urban surface roughness, magnitude of the UHI temperature anomaly, physical size of the

UHI temperature anomaly, and vegetation coverage. The objectives are:

a. *To demonstrate the capability of the GCE-PLACE to explicitly produce urban-induced circulations and cloud-rainfall processes in response to lower boundary conditions with urban land parameterizations.*

b. *To quantify the impact of urban surface roughness on the amount and distribution of induced rainfall.*

c. *To quantify the impact of the thermal magnitude of the UHI on amount and distribution of rainfall.*

d. *To quantify the impact of the physical size of the UHI on amount and distribution of rainfall.*

e. *To quantify the impact of urban vegetation cover on amount and distribution of rainfall.*

f. *To theoretically examine and validate findings of previous ground-based UHI studies and TRMM satellite-based results of Shepherd and Pierce (2002).*

Experiments have been designed to specifically investigate objectives a.-f. The work contains several novel aspects including (1) applying urban land parameterizations in GCE-PLACE at scales less than 1.0 km to investigate urban-induced rainfall processes; (2) the investigation of thermal magnitude of the UHI on rainfall process; (3) the investigation of physical size of the UHI on rainfall processes; and the investigation of how vegetation coverage can impact UHI-induced circulations.

ii. Mesoscale Model and Land Surface Model Simulations

The MM5-PLACE model will be used to demonstrate conceptually that urban land surface characteristics can play a significant role in the *prediction* of precipitating systems using mesoscale models. This fact is particularly significant as operational forecast centers like the National Oceanic and Atmospheric Administration's (NOAA) National Center for Environmental Prediction (NCEP) continue to use mesoscale-type models for routine weather forecasting. As computer technology continues to improve, and the quantity and quality of atmospheric observations increase, the resolution of mesoscale forecast models continue to increase. White et al. (1999) evaluated the performance of the NCEP mesoscale eta (Meso Eta) model. This model became operational in 1995 and is described by Black (1994). The Meso Eta had a 29-km grid spacing. In 1998, NCEP, the Meso Eta was discontinued and the comparable Eta model changed from 48-km horizontal resolution to 32-km resolution (White et al. 1999).

At the same time, urban metropolitan areas are expanding at rates such that several United States cities possess sprawling urban landscapes greater than 32 kilometers. In figure 8, this view of urban lights from space illustrates that several urban regions comprise several gridpoints in high-resolution mesoscale models like the Eta model and MM5. We propose to run a set of baseline experiments using the MM5-PLACE (described by Lynn et al. 1998). The GCE-PLACE experiments discussed previously will serve to investigate the physical and dynamical relationships between urban land cover/use and the evolution of atmospheric circulations and rainfall. The MM5-PLACE experiments seek to demonstrate the potential impact of urban surfaces on precipitation forecasts in a mesoscale model. The model will be run in a configuration such that the highest horizontal resolution is approximately 30 km. This grid will be nested within a coarser grid (on the order of 90 km). The double-nested model domains will cover the southeastern United States (fig. 4a). The primary focus will be on a warm-season, weak synoptic forcing scenario in which the PLACE surface fluxes will drive the model initialization. The primary region of interest will be the city of Atlanta, Georgia.

We propose three basic forecast experiments run for a period of 5 days. The experiments are: 1) control run, which is the coupled MM5 and PLACE model without any designation of urban landscape in PLACE, 2) urban run, which includes urban land parameterization for Atlanta, Georgia, and 3) complex urban run, which includes urban land parameterization for Atlanta, Georgia, Montgomery, Alabama, and Birmingham, Alabama. *From these experiments, we hope to assess the general outcome, tendencies, and variations in terms of quantitative precipitation forecasting (QPF).*

4. To develop a robust education and public outreach plan (EPO) that will include:

3. CONCLUSIONS

This study is an interdisciplinary investigation of land use and land cover change (e.g. urbanization) and its impact on precipitation. It demonstrates the integration of space-based remote sensing, field measurements, and numerical modeling to address a problem that is typical of the cross-system interactions of the Earth system. Future results will be reported in refereed journals, conferences, and other relevant forums. The investigators also hope for future collaborations with other interested scientists in this area.

4. REFERENCES

Baik, J.-J., Y.H. Kim, and H.Y. Chun, 2001: Dry and moist convection forced by an urban heat island. *J. Appl. Meteor*., 40, 1462-1475.

Baker, R.D., B. Lynn, A. Boone, W.K. Tao, and J. Simpson, 2001: The influence of soil moisture, coastline curvature, and land-breeze circulations on sea-breeze-initiated precipitation. *J. of Hydrometeor*., 2, 193-211.

Balling, R., and S. Brazel, 1987: Recent changes in Phoenix summertime diurnal precipitation patterns. *Theor. Appl. Climatol*., 38, 50-54.

Bornstein, R., and Q. Lin, 2000: Urban heat islands and summertime convective thunderstorms in Atlanta: three cases studies. *Atm. Env*., 34, 507-516.

Bouvette, T., J.L. Lambert, and P.B. Bedient, 1982: Revised rainfall frequency analysis for Houston. *J. of Hydraulics Division*, Proceedings of the American Society of Civil Engineers, Vol. 108, 515-528

Changnon, S.A., 1968: The LaPorte weather anomaly-fact or fiction? *Bull. Amer. Meteor. Soc*., 49, 4-11.

Changnon, S.A., 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.

Changnon, S.A, 1979: Rainfall changes in summer caused by St. Louis. *Science*, 205, 402-404.

Changnon, S.A, 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.

Changnon, S.A, 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.

Changnon, S.A, 1992: Inadvertent weather modification in urban areas: Lessons for global climate change. *Bull. Amer. Meteor. Soc*., 73, 619-627.

Culliton, T., M. Warren, T. Goodspeed, D. Remer, C. Blackwell, and J. McDonough, 1990: 50 Years of population change along the nation's coasts 1960-2010: The second report of a coastal trends series. Stratetig Assessment Branch, Oceans Assessments Division, Office of Oceanography and Marine Assessment, National Ocean Service, NOAA, Rockville, Maryland 20852, 41 pp.

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 the10th prospectus development team of the U.S. Weather Research Program. *Bull. Am. Meteor. Soc*., 81, 2047-2064.

Grell, G.A., J. Dudhia, and D.R. Stauffer, 1994: A description of the fifth-gneneration Penn State/NCAR Mesoscale Model (MM5). NCAR Tech. Note NCAR/TN-398+STR, 122 pp.

Hafner, J, and S. Kidder, 1999: Urban heat island modeling in conjunction with satellite-derived surface/soil parameters. *J. Appl. Meteor*. 38, 448-465.

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.

Hoogenboom, G., 1996: The Georgia automated environmental monitoring network. Proceedings of the 22nd AMS Conference on Agriculture and Forest Meteorology, Atlanta, GA., 343-346.

Howard, L., 1833a: *Climate of London deduced from meteorological observations*. 3d ed. Vol. 1. Harvey and Darton, 348 pp.

Huff, F. A., and S.A. Changnon, 1972a: Climatological assessment of urban effects on precipitation at St. Louis. *J. Appl. Meteor*., 11, 823-842.

Huff, F. A., and J.L. Vogel, 1978: Urban, topographic and diurnal effects on rainfall in the St. Louis region. *J. Appl. Meteor*. 17, 565-577.

Huff, F. A., 1986: Urban hydrological review. *Bull. Amer. Meteor. Soc*., 67, 703-712.

Jauregui, E., and E. Romales, 1996: Urban effects on convective precipitation in Mexico City. *Atm. Env*., 30, 3383-3389.

Kummerow, C, J. Simpson, O. Thiele, W. Barnes, A.T.C. Chang, E. Stocker, R.F. Adler, A. Hou, R. Kakar, F. Wentz, P. Ashcroft, T. Kozu, Y. Hong, K. Okamoto, T. Iguchi, H. Kuroiwa, E. Im, Z. Haddad, G. Huffman, B. Ferrier, W.S. Olson, E. Zipser, E.A. Smith, T.T. Wilheit, G. North, T. Krishnamurti, and K. Nakamura, 2000: The status of the Tropical Rainfall Measuring Mission (TRMM) after two years in orbit. *J. Appl. Meteor*., 39, 1965-1982.

Landsberg, H.E., 1970: Man-made climate changes. *Science*, 170, 1265-1274.

Lynn, B.H., W.-K. Tao, and P. Wetzel, 1998: A study of landscape-generated deep moist convection. *Mon. Wea. Rev*., **126**, 928-942.

Manley, G., 1958: On the frequency of snowfall in metropolitan England. *Quart. J. Roy. Meteor. Soc*., 84, 70-72.

McCumber, M., and R.A. Pielke, 1981: Simulations of the effects of surface fluxes of heat and moisture in a mesoscale numerical model. 1: Soil Layer. *J. Geophys. Res*., **86**, 9929-9938.

National Aeronautics and Space Administration, 2000: Understanding earth system change: NASA's Earth Science Enterprise research strategy for 200-2010., 55 pp.

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.
Orville et al., 2001: Enhancement of cloud-to-ground lightning over Houston Texas. *Geophys. Res. Ltr.,* 28, 2597-2600.

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.

Pielke, R.A., G.A. Dalu, J.S. Snook, T.J. Lee, and T.G.F. Kittel, 1991: Nonlinear influence of mesoscale land use on weather weather and climate. *J. Climate*, **4**, 1053-1069.

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.

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.

Shepherd, J.M., and S.Burian, 2003: A downscaling analysis of the urban influence on rainfall: TRMM satellite component. Proceedings of the 12th Conference on Satellite Meteorology and Oceanography, Long Beach, CA.

Shepherd, J. M., H.F. Pierce, and A.J. Negri, 2002: Rainfall Modification by Major Urban Areas: Observations from Spaceborne Rain Radar on the TRMM Satellite. *J. Appl. Meteor*., 41, 689-701.

Tao, W.-K., and J. Simpson, 1993: Goddard Cumulus Ensemble Model. Part I: Model description. *TAO*, **4**, 35-72.

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.

Wetzel, P., and A. Boone, 1995: A Parameterization for Land-Atmosphere-Cloud Exchange (PLACE): Documentation and testing of a detailed process model of the partly cloudy boundary layer over a heteorogeneous land. *J. Climate*, **8**, 1810-1837.

White, B.G., J. Paegle, W.J. Steenburgh, J.D. Horel, R.T. Swanson, L.K. Cook, D.J. Onton, and J.G. Miles, 1999: Short-term forecast validation of six models. *Wea. Forecasting*, **14**, 84-108.

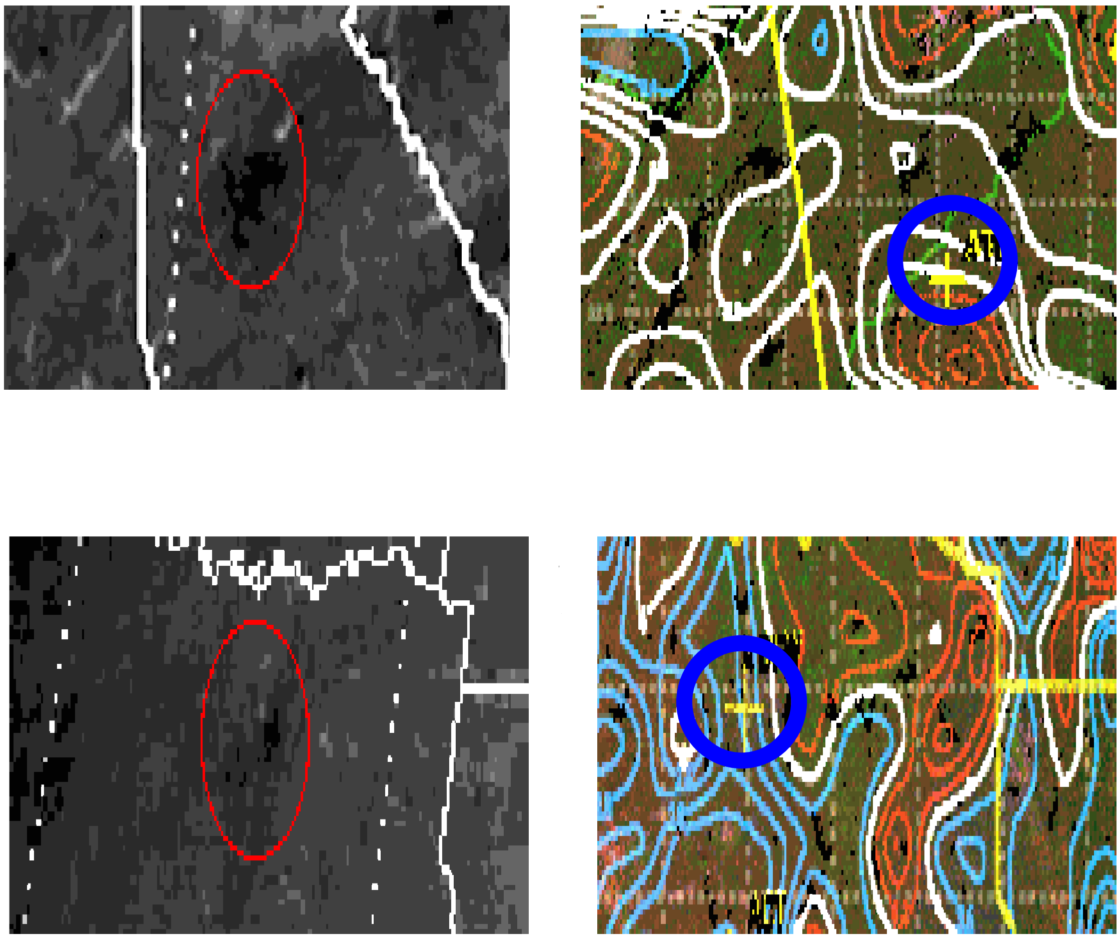

Figure 1-Results from Shepherd et al. (2002). Top Panel-Atlanta area. Bottom Panel-Dallas Area. Red Circles indicate the 3.9-micron IR signature of the urban heat islands. Blue circles indicate location of Dallas and Atlanta, respectively. Contour plots depict the 15-month warm season analysis of mean rainfall rates at a height of 2.0-km using 0.5° resolution TRMM PR data. Values in red are greater than 4.4 mm/h. Values in blue are less than or equal to 3.6 mm/h. High rainfall anomalies are located in the climatological downwind regions of Atlanta and Dallas, respectively.

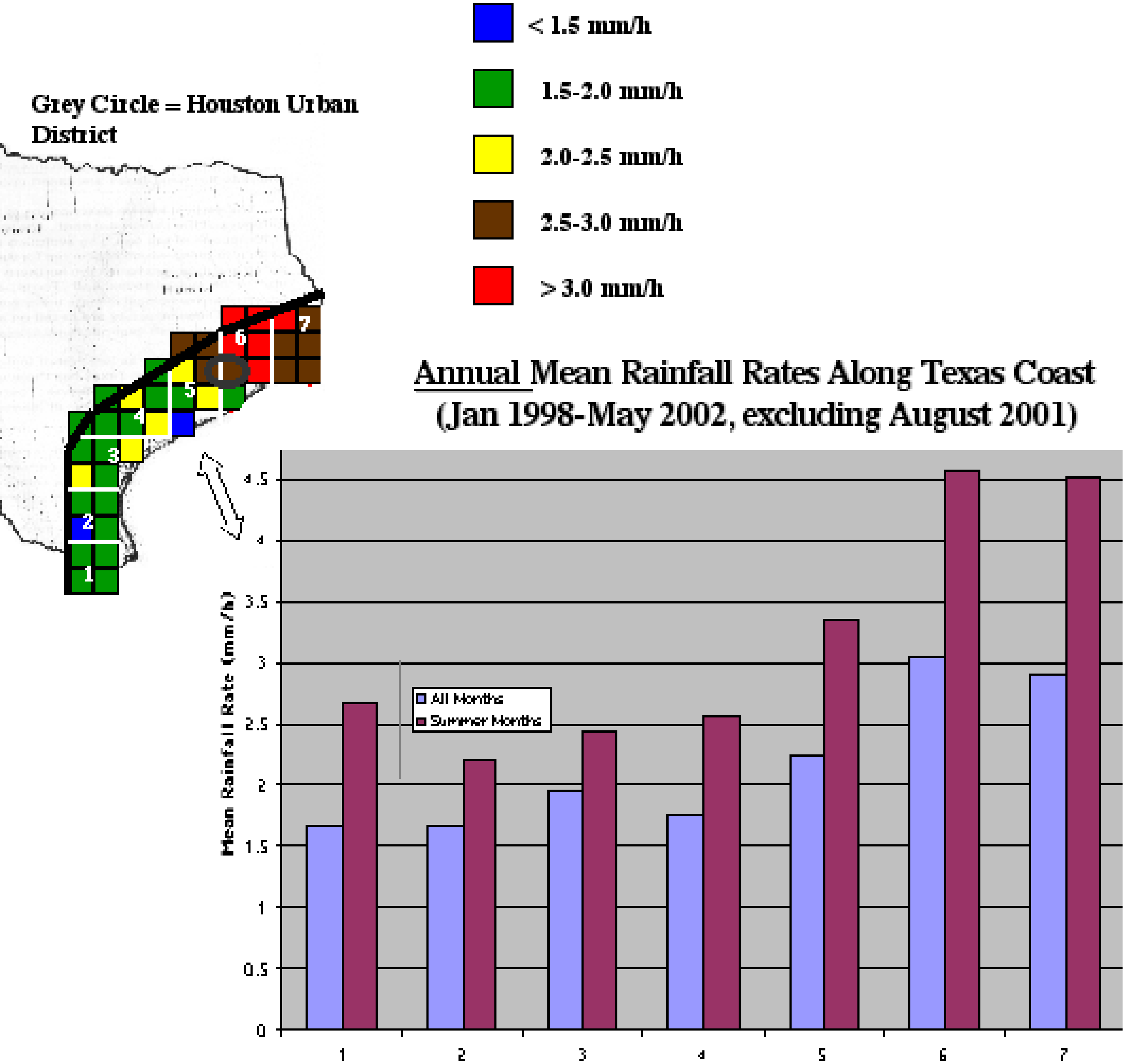

Figure 2-Mean rainfall rates over the 52-month study period (TRMM-derived) in the seven coastal zones plotted for all months and the summer.

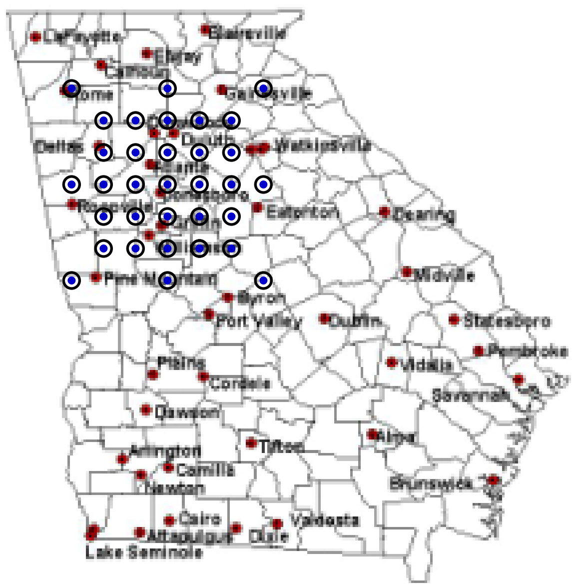

Figure 3-Potential layout for the NASA-CAU Urban Rainfall Network (blue dots). Red dots are the GAEMN Network.