

J. Marshall Shepherd, NASA/GSFC

Michael Manyin, Science Systems and Applications, Inc.

Dmitry Messen, Houston-Galveston Area Council

1. Introduction

The U.S. Climate Change Science Program (CCSP, 2003) has identified land use/land cover change as one of the key human-induced modifiers of global systems with a high degree of uncertainty in terms of impacts on climate change. A sample of major findings of the United Nations' study "World Urbanization Prospects: The 2002 Revision" (UNPD, 2002) illustrate the expected growth in urban areas:

- *Urban areas in the developing world are growing very rapidly.*
- *The urbanization process will continue worldwide.*
- *Urbanization impacts the whole hierarchy of human settlements.*

There is increasing evidence that urbanization can have a significant feedback on the climate system (Shepherd and Jin, 2004). In this paper we present a future regional weather scenario based on anticipated urban growth, in a manner analogous to current carbon dioxide projection scenarios.

Historical and recent research continues to show credible evidence that surface temperature increases (Kalnay and Cai, 2003) cloud enhancement (Inoue et al. 2004), and precipitation anomalies (Shepherd, 2005) may be linked to urban environments. We were motivated to ask the question: How will future urban scenarios further change regional climate or will such growth create new types of microclimates? *Conceptually, our approach is similar to the current body of climate change work involving carbon dioxide.* In that work, researchers assess the future climate state after differing amounts of initial carbon dioxide input.

This work is collaboration with the Houston-Galveston Area Council (H-GAC), which projected urban growth out to the year 2025 for the Houston metropolitan area. The projected growth in the Houston urban area was based on simulations from the UrbanSim model (Waddell, 2002). The model implements a perspective in which urban development is a dynamic process resulting from the interaction of many actors making decisions within the urban markets for land, housing, non-residential space and transportation. By treating urban development as the interaction between market behavior and governmental realistic projections, thereby

increasing its utility for assessing the impacts of alternative governmental plans and policies related to land use and transportation.

2. Methodology

The PSU/NCAR mesoscale model (MM5) release 3-7, used for this study, was developed in cooperation with The Pennsylvania State University and the University Corporation for Atmospheric Research (Grell et al. 1994, Grell et al. 2000). MM5 is a limited-area, nonhydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale atmospheric circulation. It contains sophisticated microphysics, radiation, and turbulence capabilities and is compatible with several land surface models.

The NOAA Land-Surface Model (Sridhar et al. 2003) is the primary land surface model (LSM) used in this study. It is a unified model between the National Center for Atmospheric Research, NOAA's National Center for Environmental Prediction (NCEP), and the Air Force Weather Agency (AFWA). The NOAA LSM originally used in MM5 had an overly simplified urban representation, which merely increased the roughness length and reduced surface albedo for urban land use. Release 3-7 of MM5 includes a more robust urban parameterization introduced by Liu and colleagues [11]. It includes: 1) increasing the roughness length from 0.5 m to 0.8 m to represent turbulence generated by roughness elements and drag due to buildings; 2) reducing surface albedo from 0.18 to 0.15 to represent the shortwave radiation trapping in the urban canyons; 3) using a larger volumetric heat capacity of $3.0 \text{ J m}^{-3} \text{ K}^{-1}$ for the urban surface (walls, roofs, and roads) which usually consist of concrete or asphalt materials; 4) increasing the value of soil thermal conductivity to $3.24 \text{ W m}^{-1} \text{ K}^{-1}$ to parameterize large heat storage in the urban surface and underlying surfaces, and 5) reducing green vegetation fraction over urban city to decrease evaporation, 6) anthropogenic heating associated with energy consumption by human activities; and 7) a very thin bucket model for evaporation and runoff from road surface.

Three fixed, nested grids were used in this study. The inner two grids were two-way interactive. The fine grid (grid 3) explicitly resolved deep moist convection. Grid 3 had grid spacing of 1.5 km, 151 x 151 horizontal grid points, and a time step of 3.33 s. The coarser grids simulated the general synoptic and mesoscale setting. Grid 2 had 4.5 km grid spacing with 100 x 100 horizontal grid points and a time step of 10 s. Grid 1 had 13.5 km grid spacing with 68 x 68 horizontal grid points and a time step of 30 s. The three grids were centered over

Corresponding Author: Dr. J. Marshall Shepherd, Geography Department, University of Georgia
Athens, GA 30602

mshpherd@uga.edu (after January 6, 2006)

marshall.shepherd@nasa.gov (before January 1st)

Houston, Texas. There were 23 vertical sigma layers, and the total depth of the model atmosphere was 14.6 km. Each nest was initialized with its own separate input data, rather than interpolating coarser data from the parent domain. All nests were started at the same time, so the initialization data sets were not in danger of conflicting with an evolving simulation. MM5 atmospheric fields, sea surface temperatures, and soil data were initialized with gridded analyses from the NCEP Eta model for 25 July 2001 (12 UTC) to 27 July 2001 (12 UTC).

Planners at HGAC aggregated the H-GAC data from its initial resolution of 1000 x 1000 sq ft to the 1.5 km resolution of the innermost MM5 domain. The result was a vector of 25 values for each MM5 grid box, representing the percent of each development type present. The 25 categories of development included various densities of residential, commercial, industrial and institutional land uses, along with vacant land, and "other" (airports, water, etc).

For each grid box in which the total percentage of H-GAC categories 1 through 23 was 50% or greater, the grid box was designated URBAN in the "Urban 2025" land-use data. All other grid boxes in the "Urban 2025" data were assigned values from the standard United States Geological Survey (USGS) land-use for that region. Once the land-use for the innermost MM5 domain was modified in this way, the parent domains were similarly changed. We employ a hypothetical treatment for urban growth so our constraints for urban use are not too conservative.

3.0 Results and Conclusions

We used the projected land use to initialize the MM5 mesoscale model coupled to the NOAA land surface model. The approach was to simulate the July 25-26, 2001 case day. On this particular day, there was clear evidence that the urban environment interacted with sea-breeze forcing to produced enhanced rainfall over and downwind of Houston. We conducted a sensitivity run by replacing the standard urban coverage with the 2025 urban land use scenario to determine how the precipitation and cloud field would have evolved differently during July 25-26, 2001. We conducted another sensitivity run (NOURB) in which all urban areas were replaced with dry-land/cropland areas, while all other parameters for the case day were unchanged. Figure 1 represents the land use for the experiments CURRENT (e.g. 1992 USGS 25-class land cover) and 2025 Scenario (e.g. 2025 HGAC-UrbanSim projected growth), respectively.

Figure 2a shows the accumulated rainfall (cm) for the CURRENT and 2025 urban land use scenarios at 2140 UTC. Clearly, the 2025 scenario produces a more widespread and heavier precipitation over the expanded urban area. Values exceed 7.5 cm in the 2025 experiment as compared to values of the order of 4.0 cm in the CURRENT run. We also found that the 2025 scenario results in a more sustained rainfall event than the CURRENT scenario. Figure 2b shows that prior to the onset of rainfall (near 1819 UTC), the 2025 urban

scenario also produced more cloud cover. Cloud cover fraction has implications for the amount of rainfall that develops but also has implications for climate sensitivity parameters like the radiation budget and associated energy exchanges between the atmospheric-terrestrial interfaces. An examination of 2-m shelter height air temperatures at 1700 UTC clearly indicates that the "urban heat island" is also more expansive in a 2025 scenario.

Results strongly suggest that the 2025 Houston urban area will be in a "wetter climate" regime. To examine this notion, we calculated the accumulated rainfall budget for all model grid points classified as "urban" in the 1.5 km resolution model domain. The analysis was conducted for the CURRENT and 2025 experiments. We also conducted the analysis for two more cases: (1) using results from the CURRENT experiment, the total accumulated rainfall, in urban and non-urban grid boxes within the projected 2025 urban area was calculated and (2) using results from the NOURB experiment, the total accumulated rainfall within the projected 2025 urban area was calculated.

In terms of sheer numbers, the 2025 case produces a factor of 9 times greater amount of rainfall in the urban portions of the domain. Because the 2025 urban area is so much larger, we normalized the accumulated rainfall by the number of urban grid points to get a more meaningful comparison. Even with the normalization factor, the 2025 case produces a factor of 2.2 times greater amount of rainfall. Essentially, the 2025 case has doubled the average rainfall produced within urban grid boxes by merely changing the expansiveness of the urban land use in the initial condition. The CURRENT variation and the NOURB analysis were conducted to verify that our increased numbers were not simply related to aggregation over a larger area. It is clear that there is something fundamentally unique about the 2025 rainfall scenario. Time series analyses indicate that the 2025 case generates rainfall earlier than the CURRENT case and that rainfall is more sustained.

The results of this study (table 1) indicate that the larger urban environment in the 2025 scenario acts as an "island" generating its own convergence zone and urban circulation similar to the sea breeze circulation in the region. This sustained thermodynamic and convergence source enables sustained and vigorous convection in conjunction with sea breeze forcing. In the relatively smaller CURRENT scenario, the city also generates confluent and convergent flow but the convergence is concentrated on the downwind edge of the city (e.g. northwest in this case). It is hypothesized that a combination of confluent flow blowing through the city from the sea-bay breeze and split-flow around the city converges on the northwest edge. Interestingly, the split-flow erodes as the urban area increases. This suggests that larger urban areas will result in greater precipitation and clouds over the city and the immediate metropolitan area rather than downwind as previous studies have shown. We should note that the time frame and scope of these results is limited and should only be considered preliminary until more rigorous testing is conducted.

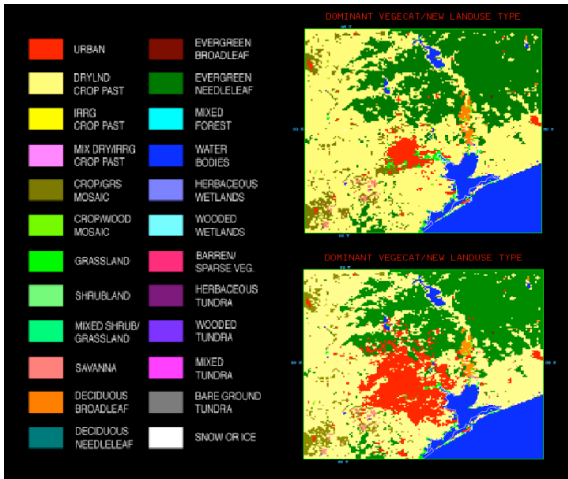


Figure 1-Land use inputs for MM5-NOAH simulations based on USGS 25-category classification. Top panel represents 1992 Houston urban land use (CURRENT) experiment, and the bottom panel represents 2025 Houston urban land use (2025) experiment.

There is increasing evidence that large coastal cities, like Tokyo, Japan and Houston, Texas, can influence weather through complex urban land use-weather-climate feedbacks. An engineering study (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 Houston, which covers an area of 937 km². Another more recent study (Burian and Shepherd, 2005) used a dense rain gauge network to show statistically significant enhancement to percent occurrence of rainfall in the Houston area. They also showed that the diurnal cycle of rainfall in Houston has also shifted from pre-urban to post-urban time periods. A related study (Shepherd and Burian, 2003) used spaceborne radar-estimated rainfall rates and ground-based gauge data to identify warm season, city and downwind anomalies in precipitation for a major coastal city. They hypothesized that dynamic processes related to the urban heat island (UHI) and enhanced mechanical turbulence in cities interacting with the sea-bay breeze produces a preferred region for convective development in the metropolitan Houston area and regions downwind. A third study (Orville et al. 2001) used 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.

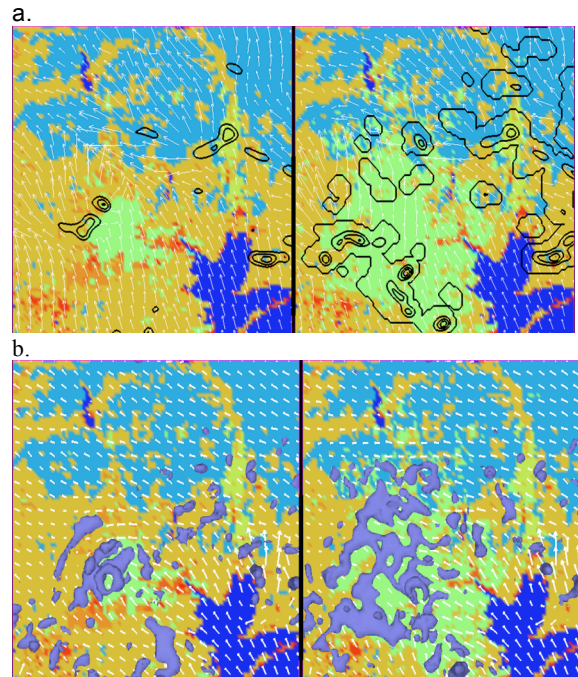


Figure 2a-b-Sensitivity experiments for CURRENT (left) and 2025 (right) experiments. (a) Top-mean accumulated rainfall (cm) in contour intervals of 2.0 cm at time 2140 UTC. (b) Middle-cloud water content isosurfaces (purple) greater than 0.1 g/kg at 1819 UTC. In panels a. and b., the underlying data is the albedo and the vectors represent the 300 m level wind.

As concern grows about the impact of anthropogenic and natural processes on climate change, water cycle accelerations, and precipitation variability; it is important to place urban processes into the context of regional and global climate system processes. The debate has generally shifted from "can urban areas affect precipitation?" to "characterizing how and why it affects rainfall?" As urban surfaces proliferate, it is not unreasonable to expect similar changes in meteorological and climate conditions similar to what have been found in this study. Future meteorological and climate modeling systems must adequately resolve urban surfaces to place their influences in the proper context.

Table 1-Model Output for Accumulated Rainfall in Model Experiments

<i>Model Experiment</i>	<i>Total # of Urban Gridpoints</i>	<i>Total Accumulated Rainfall (cm) in Urban Gridpoints</i>	<i>Total Accumulated Rainfall (cm) Normalized by # of Urban Gridpoints</i>
2025 Projected Urban Land Use	2447	1306.09	0.533
CURRENT Land Use (USGS 1992)	618	143.3	0.232
CURRENT (Total Rainfall over Projected 2025 Surface Area only)	2447	813.5	0.332
No Urban Surface (Gridpoint Rainfall over Projected 2025 Surface Area only)	2447	586.0	0.239

References and Notes

- Bouvette, et al., 1982 *J. of Hydraulics Division*, Proceedings of the American Society of Civil Engineers, **Vol. 108**, 515.
- Burian, S. and J. M. Shepherd, 2005: *Hydrological Processes: Special Issue on Rainfall and Hydrological Processes*, **19**, 1089.
- Grell, G.A. J. Dudhia, and D.R. Stauffer, 1994: *NCAR Tech. Note NCAR/TN-398+STR*, 122pp,
- Grell, et al., 2000: *Atmospheric Environment*, **34**, 1435.
- Inoue, T. and F. Kimura, 2004, *Geophys. Res. Lett.*, **31**, L05103, doi: 10.1029/2003GL018908
- Kalnay, E. and M. Cai, 2003, *Nature*, **423**, 528.
- Liu, et al., 2004: 20th Conference on Weather Analysis and Forecasting/16th Conference on Numerical Weather Prediction.
- Orville et al. 2001, *Geophys. Res. Lett.*, **28**, 2597.
- Shepherd, J.M, and M. Jin, 2004: *EOS*, **85**, 227.
- Shepherd, 2005 *Earth Interactions*, **Vol. 9, No. 12**, 1.
- Sridhar, V., R.L. Elliott, and F. Chen, 2003: *J. Hydrol.*, **Vol. 280, No.1-4**,105.
- Strategic Plan for the Climate Change Science Program Final Report, 2003, 221 pp.
- United Nations Population Division, 2002, *World Urbanization Prospects: The 2001 Revision*, 182 pp.
- Waddell P, 2002: Preprint of an article that appeared in the *Journal of the American Planning Association*, **Vol. 68 No. 3**, 297.

Acknowledgements: The authors acknowledge the support of NASA's Precipitation Measurement Missions program manager, Dr. Ramesh Kakar.