Popular Summary

Projected Regional Climate Changes in 2025 Due to Urban Growth

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By 2025, 60 to 80 percent of the world's population will live in urban environments. Additionally, the following facts published by the United Nations further illustrates how cities will evolve in the future.

- *Urban areas in the developing world are growing very rapidly.* The urban growth rate will continue to be particularly rapid in the urban areas of less developed regions, averaging 2.4 per cent per year during 2000-2030, consistent with a doubling time of 29 years.
- *The urbanization process will continue worldwide.* The concentration of population in cities is expected to continue so that, by 2030, 84 percent of the inhabitants of more developed countries will be urban dwellers.
- *Urbanization impacts the whole hierarchy of human settlements.* In 2000, 24.8 per cent of the world population lived in urban settlements with fewer than 500,000 inhabitants and by 2015 that proportion will likely rise to 27.1 per cent.

We ask the hypothetical question, "Does Urbanization rank alongside Carbon Dioxide Emissions as a primary anthropogenic cause for climate change?" The answer to this question is likely no, but there is increasing evidence that urbanization can have a significant effect on clouds, precipitation, storms, and runoff. Furthermore, the U.S. government's climate progam has identified land use change as one of the key forcing functions which affect climate, but to what degree scientists are largely uncertain. 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. We use an urban growth model to project the growth of Houston, Texas from 1992 to 2025. Then, we initialize a coupled weather-land surface model with the 2025 urban land use data. Our results indicate that regional cloud patterns, precipitation, and temperatures will be significantly different in the coastal-urban region around Houston given the projected urban growth. *The major result suggests that simply changing the initial urban land use to project 2025 levels produces a significantly wetter regional climate and significantly more cloud cover,* which has implications for climate change arguments. Based on our findings, it is easy to understand why there is interest in the rapidly urbanizing world and its influence on weather, climate, and water cycle processes.

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Abstract:

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Does Urbanization rank alongside Carbon Dioxide Emissions as a primary anthropogenic cause for climate change? The answer to this question is likely no, but there is increasing evidence that urbanization can have a significant feedback on the climate system. Furthermore, the U.S. Climate Change Science Program has identified land use change as one of the key forcing functions which affect climate, but to what degree scientists are largely uncertain. 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. We use an urban growth model to project the growth of Houston, Texas from 1992 to 2025. Then, we initialize a mesoscale atmospheric-land surface model with the 2025 urban land use data. Our results indicate that regional cloud patterns, precipitation, and temperatures will be significantly different in the coastal-urban region around Houston given the projected urban growth. These findings have implications for ongoing discussions on what factors will contribute to changes in climate and Earth's water cycle processes.

Introduction

The U.S. Climate Change Science Program (CCSP) [1] has identified land use/land cover change (LULC) 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 2001 Revision" [2] illustrate the expected growth in urban areas:

- *Urban areas in the developing world are growing very rapidly.* The urban growth rate will continue to be particularly rapid in the urban areas of less developed regions, averaging 2.4 per cent per year during 2000-2030, consistent with a doubling time of 29 years.
- *The urbanization process will continue worldwide.* The concentration of population in cities is expected to continue so that, by 2030, 84 percent of the inhabitants of more developed countries will be urban dwellers.
- *Urbanization impacts the whole hierarchy of human settlements.* In 2000, 24.8 per cent of the world population lived in urban settlements with fewer than 500,000 inhabitants and by 2015 that proportion will likely rise to 27.1 per cent.

Does Urbanization rank alongside Carbon Dioxide Emissions as a primary anthropogenic cause for climate change?? The answer to this question is likely no, but there is increasing evidence that urbanization can have a significant feedback on the climate system [3]. 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.

Recent research continues to show credible evidence that surface temperature increases [4], cloud enhancement [5], and precipitation anomalies [6] 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 a 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 from 1992 to 2025 was based on simulations from the UrbanSim model [7]. The model implements a perspective on urban development that represents 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 actions, UrbanSim is designed to produce highly realistic projections, thereby increasing its utility for assessing the impacts of alternative governmental plans and policies related to land use and transportation.

Methodology

The PSU/NCAR mesoscale model (MM5) release 3-7, used for this study, was developed in cooperation with The Pennsylvania State University (Penn State) and the University Corporation for Atmospheric Research (UCAR) [8,9]. 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 NOAH Land-Surface Model [10] is the primary land surface model (LSM) used in this study. It is a unified model between the National Center for Atmospheric Research (NCAR), NOAA's National Center for Environmental Prediction (NCEP), and the Air Force Weather Agency (AFWA). The NOAH LSM originally used in MM5 had an overly simplified urban representation, which merely increases the roughness length and reduces surface albedo for urban landuse. 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 J m^{-3} K^{-1} for the urban surface (walls, roofs, and roads) which is usually consisted of concrete or asphalt materials; 4) increasing the value of soil thermal conductivity to 3.24 W m^{-3} 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. anthropogenic heating associated with energy consumption by human activities; and 6) 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 has grid spacing of 1.5 km, 151 x 151 horizontal grid points, and a time step of 3.33 s. The coarser grids simulate the general synoptic and mesoscale setting. Grid 2 has 4.5 km grid spacing with 100 x 100 horizontal grid points and a time step of 10 s. Grid 1 has 13.5 km grid spacing with 68 x 68 horizontal grid points and a time step of 30 s. The three grids are centered over Houston, Texas. There are 23 vertical sigma layers. The total depth of the model atmosphere is 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 are initialized with gridded analyses from the NCEP Eta model for 25 July 2001 (12 UTC) to 27 July 2001 (12 UTC).

The H-GAC data was aggregated from its initial resolution of 1000 x 1000 sq ft to the 1.5 km resolution of the innermost MM5 domain by planners at HGAC. The result was a vector of 25 values for each MM5 gridbox, 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 gridbox in which the total percentage of H-GAC categories 1 through 23 was 50% or greater, the gridbox was designated URBAN in the "Urban 2025" land-use data. All other gridboxes 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 domain was similarly changed. Each gridbox in the parent covers 9 gridboxes in the child. Wherever the count of URBAN gridboxes met or exceeded the count of any other land-use category in the child domain, the gridbox in the parent domain was tagged URBAN. In this manner, the lower resolution domains were updated for the "Urban 2025" case.

Results and Conclusions

We integrated the projected land use category into the MM5 mesoscale model coupled to the NOAH land surface model. The approach was to use 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 based on USGS 25-class land cover 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 interface. An examination of 2-m shelter height air temperatures at 1700 UTC clearly indicates that the "urban heat island" is 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 gridpoints 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 variations of the CURRENT experiment where (1) the total accumulated rainfall, urban or non-urban, over the projected 2025 area was calculated and (2) the total accumulated non-urban rainfall over the projected 2025 area was calculated. Table 1 summarizes these findings.

The results in table 1 are very compelling. 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. However, we normalized the accumulated rainfall by the number of urban gridpoints 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 amount of rainfall produced only because of a change in the expansiveness of the urban land use in the initial condition. The two CURRENT variations were conducted to make verify that our increase 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. Figure 3 plots a time series of the accumulated rainfall for these four scenarios. The major result is that the 2025 case generates rainfall earlier than the CURRENT case and that rainfall is more sustained.

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 [12] 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 km^2. Another more recent study [13] 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 [14] 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 [15] 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.

The results of this study 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.

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.

References and Notes

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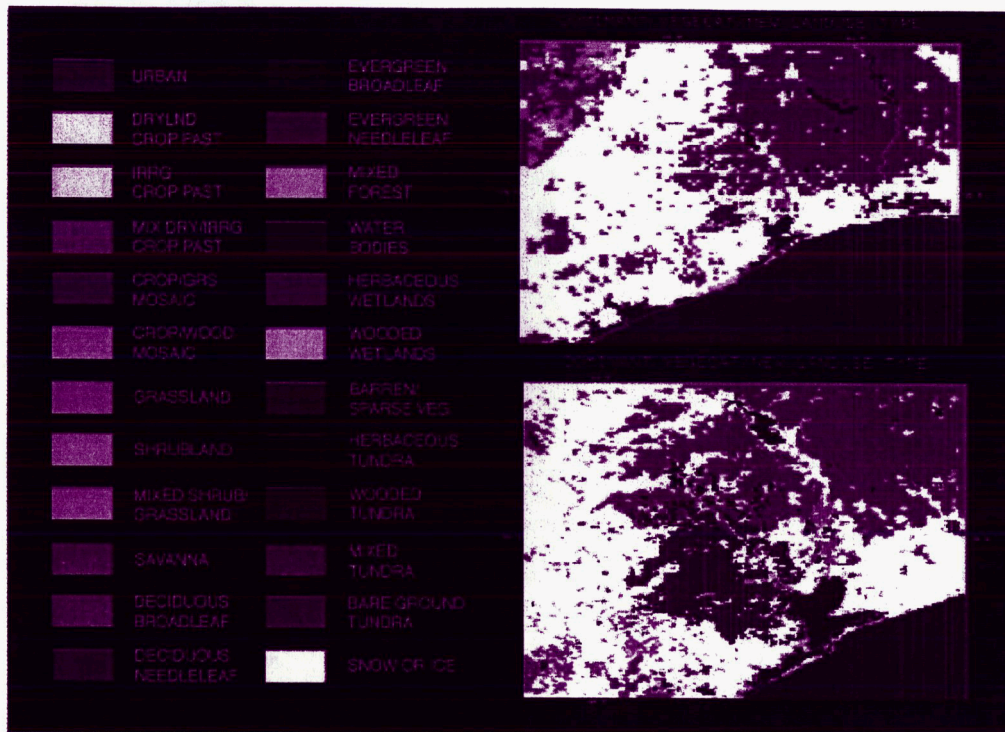15.   Orville et al., *Geophys. Res. Ltr.*, **28**, 2597 (2001).

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.

Table 2-Model Output for Accumulated Rainfall in Model Experiments

| Model Experiment	Total # of Urban Gridpoints	Total Accumulated Rainfall (cm) in Urban Gridpoints	Total Accumulated Rainfall (cm) Normalized by # of Urban Gridpoints
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
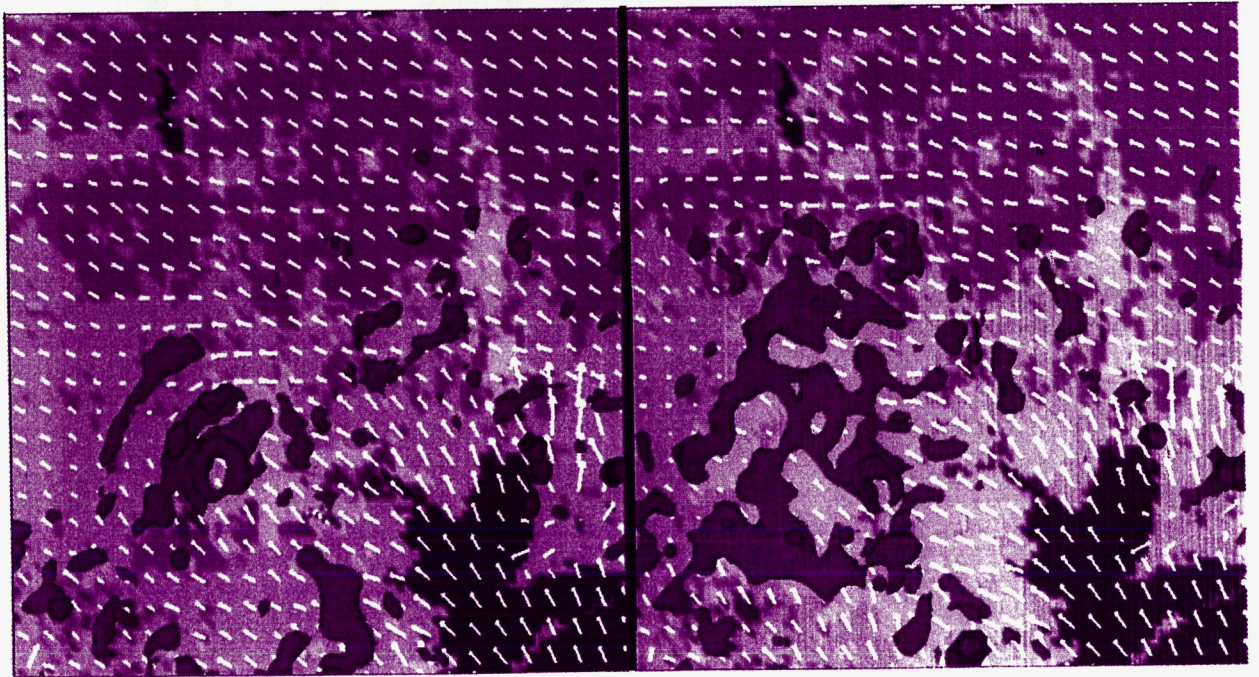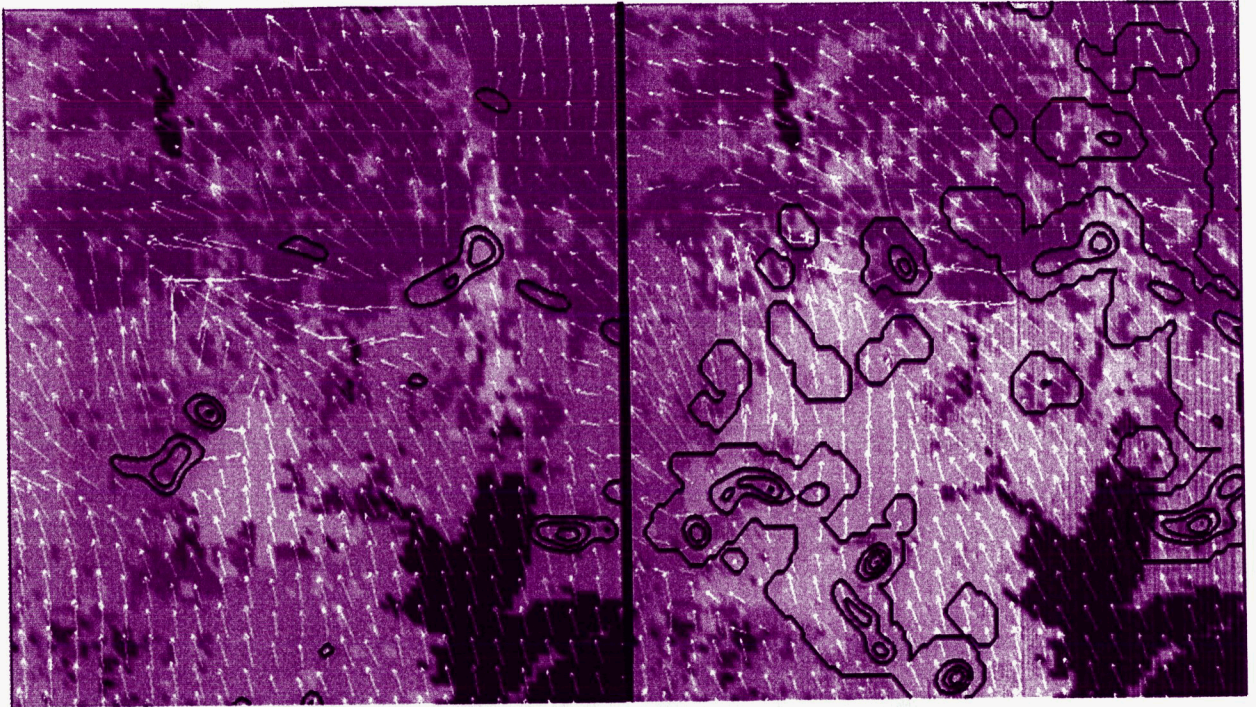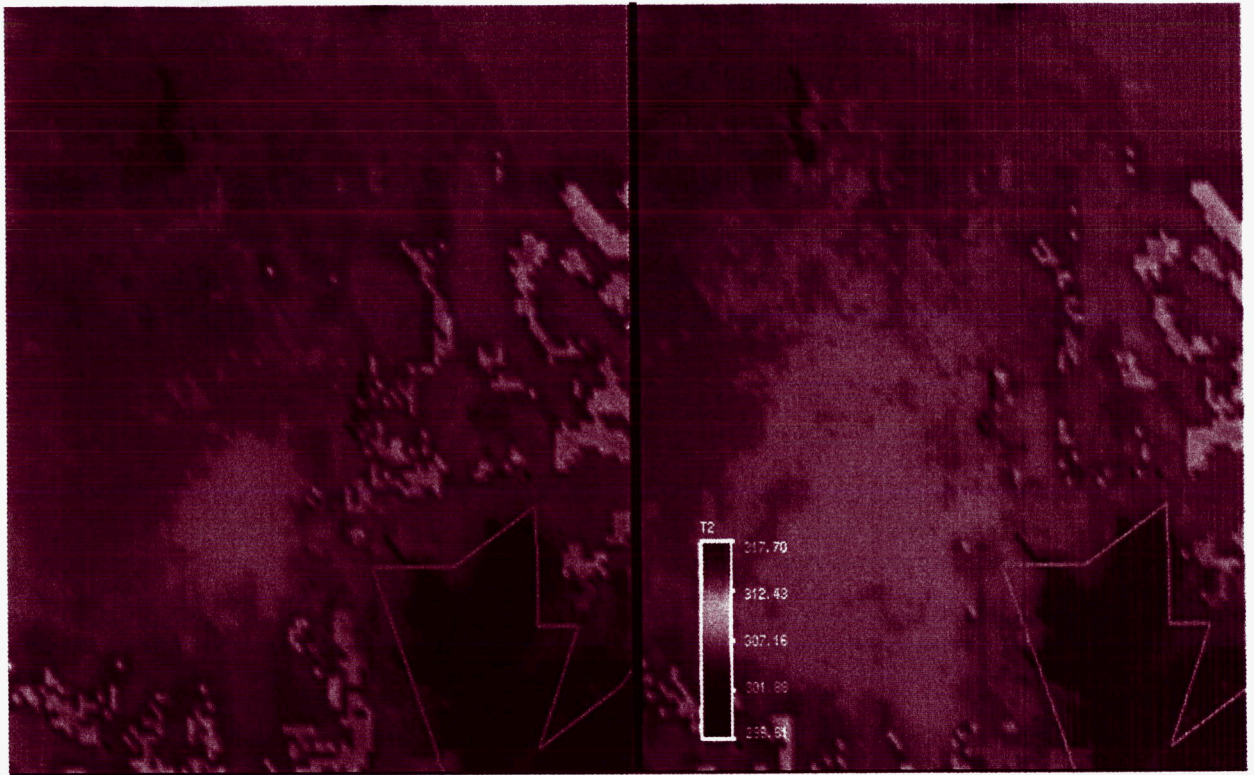
Figure 2a-c-Sensitivity experiments for CURRENT (left) and 2025 (right) experiments. (a) Top-mean accumulated rainfall (cm) in contour intervals of 2.0 cm at time 2140 UTC. (b) Middle-cloud water content isosurfaces (purple) greater than 0.1 g/kg at 1819 UTC. (c) 2-m shelter height air temperature at 1700 UTC. In panels a. and b., the underlying data is the albedo and the vectors represent the 300 m level wind.

Accumulated Rainfall (cm)

Legend:
- 2025 Project Urban Land Use
- Urban and Non-Urban-2025 Areal Coverage
- CURRENT (e.g. 1992 USGS Land Use)
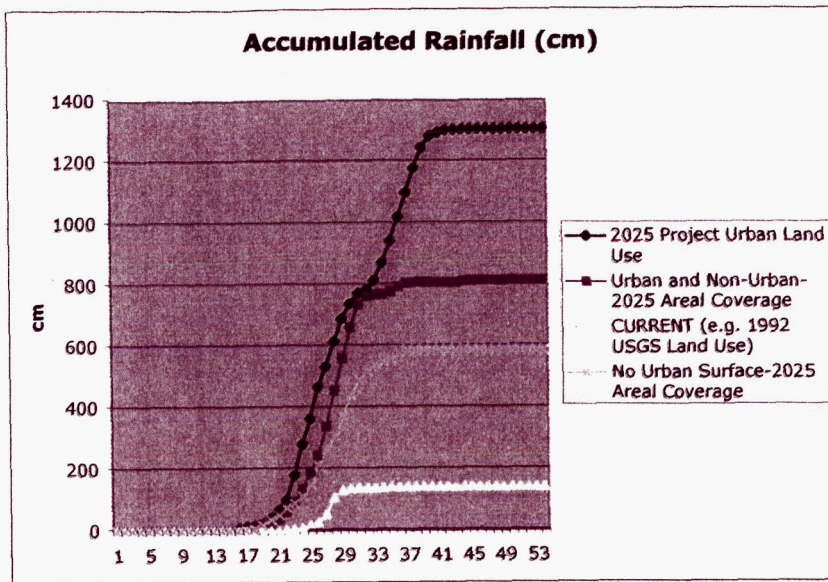- No Urban Surface-2025 Areal Coverage

Figure 3-Time series of accumulate rainfall (cm) for various model experiments. Each increment of time along the abscissa represents 20 minutes.