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# Urban growth and aerosol effects on convection over Houston Part I: The August 2000 case

G.G. Carrió *, W.R. Cotton, W.Y.Y. Cheng

*Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523, USA*

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The objective of this paper is to investigate the effects of the growth of the Houston metropolitan area on the characteristics and intensity of convection and precipitation. For this purpose, we implemented the Town Energy Budget (TEB) urban model into Regional Atmospheric Modeling System (RAMS). The Landsat Thematic Mapper National Land Cover Data (NLCD) for the Houston area corresponding to the years 1992, 2001 and 2006 were used for an objective experimental design of land-use sensitivity experiments. We analyzed the impact on two distinct groups of convective cells triggered by the sea breeze circulation on August 24 2000 and compared the model simulated precipitation to RADAR data. The first group of storms occurred southwest of the city and was not influenced by the urban cloud condensation nuclei (CCN), while the second was and occurred north of the city (downwind) a few hours later. The effect of land-use on convection and precipitation was dramatic for the storms SW of the city and it was linked to a monotonic increase in the intensity of the sea breeze. The intensification of the sea-breeze circulation when using the 1992, 2001, and 2006 NLCD land use datasets generated a monotonic increase of the total precipitated volume of 9, 11, and 25%, respectively (over a run with no city). Due to increased exposure to aerosols, the upper levels of the convective cells downwind of the city were invigorated by a greater latent heat release linked to higher amounts of liquid water transported to supercooled levels. However, precipitation did not show a monotonic behavior when we varied the intensity of the urban aerosol sources. With the highest aerosol concentrations, riming growth of ice particles became so inefficient that larger amounts of condensate was transported upwards into the storm anvil, contributing to a reduction in precipitation efficiency.


## 1. Introduction

Several early studies suggested that precipitation patterns were modified by the presence of cities (Landsberg, 1956; Stout, 1962; Changnon, 1962, 1968; Khemani and Murty, 1973). During Project Metropolitan Meteorological Experiment (METROMEX), heavier precipitation was observed downwind of the city compared to the rural surroundings, particularly in the summer months. More recent studies indicate that the rapid growth of urban areas has a significant impact on their weather and regional climate. For that reason, the Intergovernmental Panel on Climate Change (IPCC; Trenberth et al., 2007 highlighted the need for more scientific studies connecting changes in precipitation and urban-related processes. Urban development can create an energy balance vastly different from their surroundings and can significantly modify the air flow and the hydrology near the surface. The mechanisms not involving urban aerosols that may act independently or in conjunction with each other (see reviews by Shepherd (2005) and Cotton and Pielke(2009)) are the following: 1) Enhanced convergence due to an increased

* Corresponding author. Atmospheric Science Building, Office 225 Colorado State University, Fort Collins, CO 80523, USA.
*E-mail address:* carrio@atmos.colostate.edu (G.G. Carrió).

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surface roughness of urban areas leads to enhanced surface convergence over and downwind of the urban region (e.g., Hjelmfelt, 1982; Bornstein and Lin, 2000; Thielen et al., 2000; Craig and Bornstein, 2002; Rozoff and Cotton, 2003); 2) a destabilization generated by sensible and latent heat fluxes within the urban region and thermal perturbations of the boundary layer by the urban heat island (UHI) (e.g., Braham et al., 1981; Thielen et al., 2000; Baik and Kim, 2001; Shepherd et al., 2002; Shepherd, 2006; Rozoff and Cotton, 2003; Mote et al., 2007; Baik et al., 2007); 3) the urban region serves as an enhanced source of moisture (e.g., Dixon and Mote, 2003); and 4) the urban canopy diverts precipitation systems (e.g., Loose and Bornstein, 1977; Bornstein and Lin, 2000).

On the other hand, several studies link various possible effects on convection and precipitation to the urban particulate pollution that represent a source of cloud condensation nuclei (CCN). The invigoration of cloud growth (Khain et al., 2004, 2005, 2008; Lynn et al, 2005a, b; Seifert and Beheng, 2006; van den Heever et al., 2006; van den Heever and Cotton, 2007; Rosenfeld and Khain, 2008) from increased aerosol concentration slows the autoconversion rate of cloud droplets into rain drops, so that more cloud water ascends to altitudes at which the temperature is below the freezing level. The condensed water is likely to freeze and thereby releases greater amounts of latent heat. The delay in the formation of raindrop growth and ice alters the vertical profile of latent heat release and is sufficient to cause invigoration of cloud dynamics. This process has been modeled by Seifert and Beheng (2006), van den Heever et al. (2006), and van den Heever and Cotton (2007). Seifert and Beheng (2006) note, however, that if the convection is not intense enough to thrust condensate into supercooled altitude levels, then the updrafts can become water-loaded. As a result, precipitation and storm dynamics can be suppressed by increased CCN. Moreover, van den Heever and Cotton (2007) note that enhanced CCN can invigorate cumulus dynamics early during their development phase, but once low-level cold pools are modified, the resultant behavior of the system is dependent upon secondary cloud growth, which, for the case they simulated, resulted in weakened convection and reduced rainfall. Enhancing CCN concentrations has also been found to increase the mass transported out of the storm into anvil levels affecting the optical thickness and lifetime of the anvil-cirrus clouds (Carrió et al., 2007). Soon after the detachment from the storm outflow, the anvil clouds have narrower ice particle size distributions characterized by higher frequencies for smaller ice particles and lower in-cloud turbulent kinetic energy contributing to an increase of their lifetime. For reviews of aerosol effect on dynamics and microphysics of clouds see Khain (2009) and Levin and Cotton (2009).

Houston was one of the fastest growing metropolitan areas in the United States during the past three decades and therefore, it was the focus of several recent studies. The average warm-season rainfall amount registered in the urban area increased by 25% from the pre- to the post-urban time period (Burian and Shepherd, 2005). Jin et al. (2005) analyzed cloud properties and rainfall in relation to diurnal, weekly, seasonal, and interannual variations of urban aerosols. Their results for Houston indicate that in the summer, the aerosol impact may not be the primary reason for the change of urban rainfall; however, the role of aerosols remains uncertain. Fan et al. (2007) numerically studied the impact of urban aerosol with a spectral microphysics package (Khain et al., 2004) for a convective case that occurred in Houston on August 24 2000 using an idealized 2D framework. This study indicated a considerable response of macro and microphysical cloud properties to changes in aerosols and their chemical composition.

In this paper, we investigate the effects of the urban growth and the associated aerosol sources on convection over Houston. For this purpose, we implemented the Town Energy Budget (TEB) urban model into the Regional Atmospheric Modeling System developed at Colorado State University (RAMS@CSU, Pielke et al., 1992; Cotton et al., 2003). The Landsat Thematic Mapper National Land Cover Data (NLCD) for the Houston area for three years (1992, 2001, and 2006) were used for the experimental design of the land-use sensitivity experiments, including a run with “no city”. We performed a series of sensitivity runs linking CCN sources to urban cells using the same sea-breeze induced case of Fan et al. (2007) but with a more realistic 3D nested grid setup. However, our numerical experiments did not vary aerosol chemical composition. Dusek et al. (2006) presented observational evidence that it is more important to use accurate estimates of aerosol size than aerosol composition for droplet nucleation. A modeling study (Rissman et al., 2004) on the impact of aerosol composition on droplet nucleation have also found that the CCN activity is more sensitive to changes in aerosol size than composition. A brief description of the model we used is given in Section 2. In Section 3 we give the design of the numerical sensitivity experiments and initial conditions. Results and conclusions are presented in Sections 4 and 5, respectively.

## 2. Model description

The dynamical modeling framework used for this study is RAMS (Pielke et al., 1992; Cotton et al., 2003) developed at Colorado State University (RAMS@CSU). This non-hydrostatic model integrates predictive equations for the wind components, the Exner function, the ice–liquid water potential temperature, and the total mixing ratio on a vertically-stretched Arakawa C-grid.

The two-moment bin-emulating microphysical model (Saleeby and Cotton, 2004, 2008) predicts the mass mixing ratios and number concentrations of various hydrometeor species and cloud-nucleating aerosols. A large-cloud-droplet mode (drizzle drops) is considered in combination with the traditional single mode of cloud droplets. This permits the representation of the bimodal distribution of cloud droplets that is often seen in clouds (Hobbs et al., 1980). This mode plays a significant role in the collision–coalescence process by requiring droplets to grow at a slower rate rather than being transferred directly from the first cloud droplet mode to rain. There is also a significant impact of drizzle drops mode upon ice formation, because two modes now exist and are allowed to participate in homogeneous freezing nucleation, secondary ice production through the Hallett–Mossop processes, collisions with ice species. Therefore, this detailed microphysical framework is of great importance for this study as it allows a better representation of numerous microphysical mechanisms affecting the microphysical structure of the storms.