URBAN AEROSOL EFFECTS ON CONVECTIVE STORM CHARACTERISTICS

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1. INTRODUCTION

Observations indicate that precipitation and severe weather anomalies occur over and downwind of St. Louis, Missouri (Braham, 1976; Changnon, 1981; Changnon and Huff, 1986) and other urban areas (Balling and Brazel, 1987; Westcott, 1995; Orville et al., 2001; Steiger et al., 2002). The causes of these anomalies are still not well understood, in spite of good field studies and data analyses. Hypotheses include the impacts of the urban heat island (UHI) (Hjelmfelt,1982; Bornstein and Lin, 2000; Thielen et al., 2000; Baik and Kim, 2001; Craig and Bornstein, 2002; Rozoff et al., 2003) and variations in the concentrations of anthropogenic aerosols that are associated with urban regions. It is the latter effect that is the focus of the research presented here.

It is well known that enhanced cloud condensation nuclei (CCN) concentrations can result in narrower droplet spectra, thereby suppressing warm rain processes (e.g. Warner and Twomey, 1967; Warner, 1968; Rosenfeld, 1999). On the other hand, urban areas like St. Louis can also be sources of giant CCN (GCCN) or ultra-giant particles which can enhance warm rain processes (Johnson, 1976; Hindman et al., 1977a,b; Feingold et al., 1999). Also, the presence of supercooled raindrops greatly increases the rate of glaciation of cumuli as the supercooled droplets readily collect ice crystals and freeze (Cotton 1972a,b; Koenig and Murray, 1976; Scott and Hobbs, 1977), and the Hallett-Mossop, rime-splintering process is enhanced (Cotton and Pielke, 1995). The goal of the research presented here is thus to investigate the impact that variations in the concentrations of CCN and GCCN have on the microphysical, dynamical and precipitation characteristics of convective storms developing over and downwind of urban regions through the use of a mesoscale cloud-resolving model.

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2. CASE STUDY

The development of convective storms in the region of St. Louis, Missouri, on 8 June 1999 was used as the case study for this research. This day was also used by Rozoff et al. (2003) in their investigation of urban land use impacts on thunderstorms and therefore allows for a direct comparison of these effects. On this day, a number of convective events, identified as ordinary thunderstorms, occurred over and around the urban region (Figure 1). The environment was generally devoid of large-scale forcing but was warm and moist (~1500 J kg^{-1} of CAPE), with weak southwesterly mean tropospheric flow. Storms developed in the early afternoon and lasted through the early evening, producing locally heavy rain, large hail and considerable wind damage.

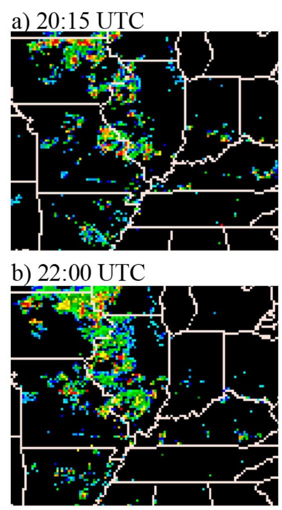

Figure 1: NEXRAD National Mosaic Imagery (obtained from NCDC) of the convective thunderstorm development in the St. Louis, MO region on 8 June, 1999.

3. METHODS

3.1 *Mesoscale Model*

The Regional Atmospheric Modeling System developed at Colorado State University (RAMS@CSU) (Pielke et al., 1992; Cotton et al., 2003) was chosen to achieve the goal stated above. The sophisticated “Town Energy Budget” (TEB) model of the urban land surface (Masson, 2000) was used to accurately represent the urban surface layer by providing such quantities as sensible heat flux, latent heat flux, momentum co-variances, albedo and emissivity to RAMS. Two-moment microphysics (Meyers et al., 1997), in which both the mixing ratio and number concentration of the hydrometeor species are prognosed was utilized. All the available microphysical species (cloud water, rain, pristine ice, snow, aggregates, graupel and hail) were activated. The concentrations of CCN, GCCN and IFN are all prognostic variables in RAMS (Saleeby and Cotton, 2004). The aerosol version of RAMS microphysics permits the simulation of aerosol sources and sinks, their activation in cloudy updrafts, and their impacts on the evolution of the precipitation process.

Three two-way interactive grids with horizontal grid spacings of 37.5, 7.5 and 1.5 km were employed. The location of these grids is shown in Figure 2. Forty variable grid levels were used in the vertical, and the model top extended to ~22 km AGL. The fine grid spacing of grid 3 allowed for the explicit simulation of convection. ETA data were used to initialize the atmospheric variables, and the simulations were conducted for 24 hours starting at 0000 UTC on 8 June 1999.

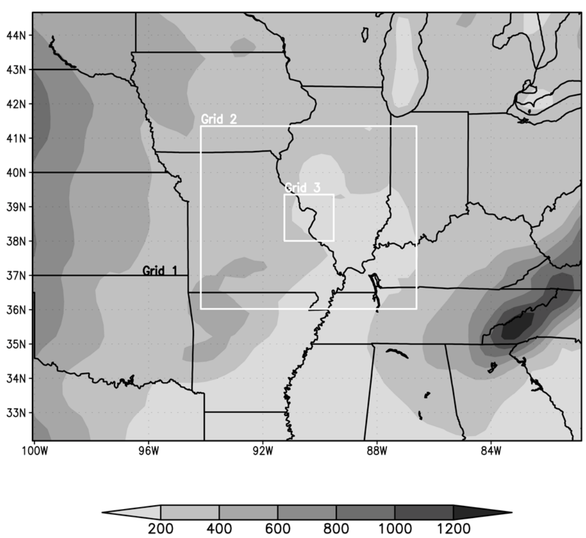

Figure 2: The topography (m) and location of grids 1 through 3 used in the simulations described in the text.

3.2 Data and Experiment Design

Rural and urban concentrations of CCN and GCCN were estimated using observations made during the Metropolitan Meteorological Experiment (METROMEX) conducted over St. Louis from 1971 to 1975 (Braham 1976; Changnon 1981). Upwind and downwind summer CCN concentrations made between 1971 and 1973 (Braham, 1974; Spyers-Duran, 1974; Auer, 1975) at 0.7% supersaturation were averaged, resulting in rural and urban CCN concentrations of 1200 cc^{-1} and 2000 cc^{-1}, respectively. GCCN (> 1 micron in radius) concentrations were obtained from volume distributions of large aerosol particles (diameters between 5 and 55 microns) upwind and downwind of St. Louis (Johnson, 1976; Braham, 1977) and combined with concentrations obtained for particle sizes between 1 and 5 microns from volume distributions presented by Komp and Auer (1978). The rural and urban GCCN concentrations were found to be 0.1 cc^{-1} and 0.2 cc^{-1}, respectively.

In the control experiment (RURAL-H) the urban region and the associated urban characteristics and heat and moisture fluxes were activated, but the entire model domain was initialized with the rural CCN and GCCN concentrations given above. Sensitivity tests were then conducted in which a continuous source function of CCN (CCN-H), GCCN (GCCN-H) and then both CCN and GCCN (URBAN-H) was activated over the urban region between the surface and ~500m AGL. The model was initialized with the rural aerosol concentrations elsewhere. A sensitivity test (NOCITY-H) was also conducted that was identical to the control simulation, except that the urban region was removed (by replacing the urban land use class with cropland, and the suburban land class with wooded grassland).

A further series of sensitivity tests were also conducted. The tests in this series were identical to those described above, except that lower background CCN (800 cc^{-1}) and GCCN (0.01 cc^{-1}) concentrations were used. The urban aerosol concentrations were the same as those used above. These tests were designed to investigate the impacts of urban aerosol on relatively “clean” rural environments. The sensitivity tests are all summarized in Table 1.

Table 1: Aerosol characteristics of the sensitivity tests described in the text.

Experiment	CCN	GCCN	CITY
High Background Aerosol Concentrations Rural: CCN 1200 cc^{-1} GCCN 0.1 cc^{-1} Urban: CCN 2000 cc^{-1} GCCN 0.2 cc^{-1}			
RURAL-H	R	R	ON
CCN-H	U	R	ON
GCCN-H	R	U	ON
URBAN-H	U	U	ON
NOCITY-H	R	R	OFF
Low Background Aerosol Concentrations Rural: CCN 800 cc^{-1} GCCN 0.01 cc^{-1} Urban: CCN 2000 cc^{-1} GCCN 0.2 cc^{-1}			
RURAL-L	R	R	ON
CCN-L	U	R	ON
GCCN-L	R	U	ON
URBAN-L	U	U	ON
NOCITY-L	R	R	OFF
R => RURAL; U=> URBAN			

4. RESULTS

The evolution of an UHI over St. Louis during the day in the control simulation (URBAN-H) is apparent in Figure 3. The heat island begins intensifying by 1600 UTC, and by 1800 UTC the temperature difference between the urban and rural surroundings is approximately 2°C. Water vapor mixing ratios are also substantially lower over the city than the surrounding rural regions. Winds become more south to southeasterly with time, and confluence of the surface winds downwind of the city increases throughout the morning. In the observations, the winds tend to be more southwesterly. Examining the same output from NOCITY-H in which the urban region has been removed, demonstrates that the UHI does not develop, and the associated variations in temperature, moisture and convergence do not occur (Figure 4).

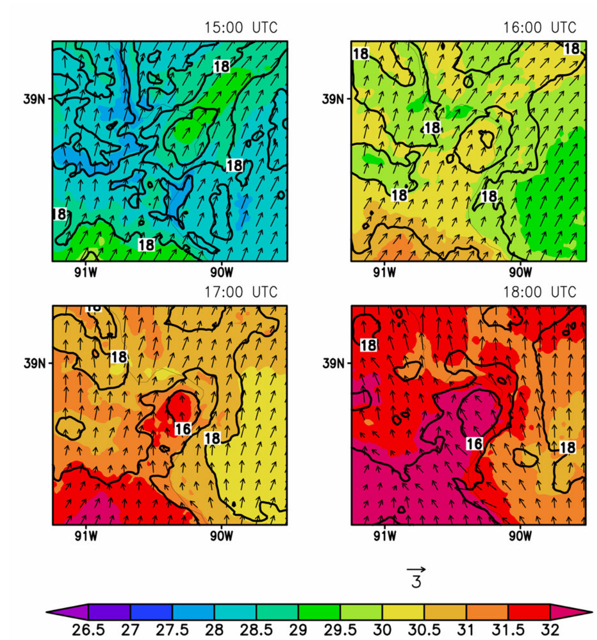

Figure 3: A time series indicating the development of the urban heat island in RURAL-H. Temperature (shaded, C), vapor mixing ratio (thick black lines, g/kg) and wind vectors (scale indicated below figures) at ~50 m AGL are shown.

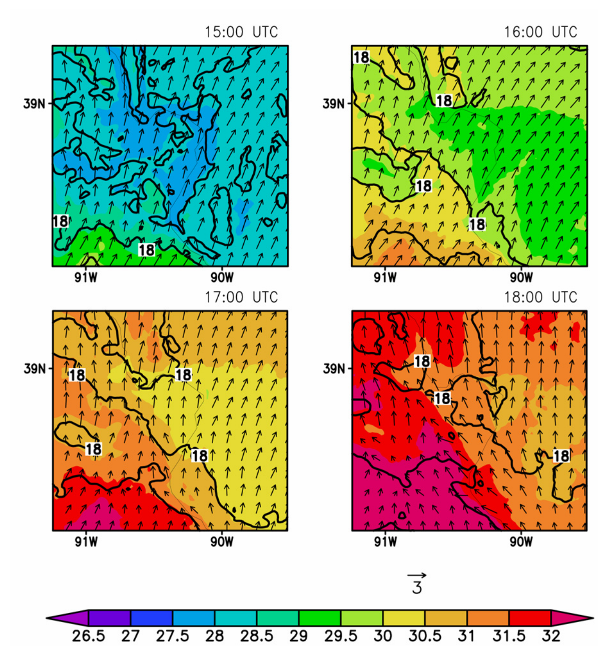

Figure 4: As for figure 3 but for NOCITY-H.

The development of the convective storms around St. Louis between 2000 UTC and 2130 UTC for the control simulation (RURAL-H), together with the low-level (~550m AGL) CCN concentration are shown in Figure 5. Convection starts to form to the southwest of the city around 1800 UTC in the simulations and by 1900 UTC deep, moist precipitating convection develops (not shown). By 2000 UTC, a storm initiates downwind (north to northwest) of the city, producing deep updrafts by 2015 UTC. The convection to the southwest of the city is also apparent. The storms downwind of the city last through 2130 UTC after which they weaken and dissipate. Overall the similarity between the radar data and the simulation is relatively good given the difficulty in accurately representing the temporal and spatial development of isolated convection, although, the simulated storms do lag the observed convection by about 2 hours, as found by Rozoff et al. (2003). Comparing Figure 5 with a similar plot for NOCITY-H (Figure 6) in which the urban region has been removed, it is apparent that the storms that develop downwind of the city in RURAL-H do not develop in NOCITY-H, while those to the southwest of the city develop in both simulations.

The updraft location and development in URBAN-H (not shown) in which both the CCN and GCCN concentrations were enhanced were similar to those in RURAL-H, although the cell downwind of the city did develop earlier in URBAN-H (2015 UTC).

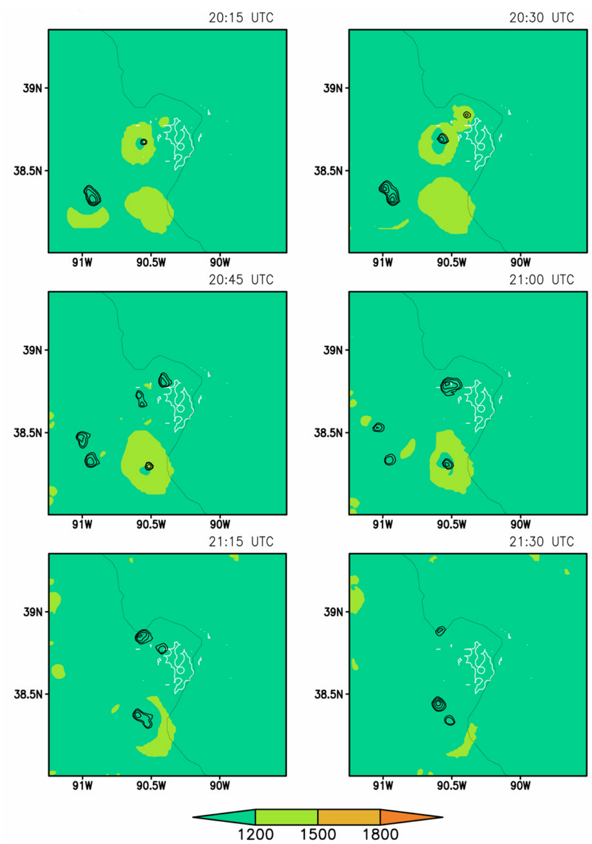

Figure 5: CCN concentration (shading, cc^{-1}) at 550m AGL, and vertical velocity (thick black lines, contour interval: 10 $m.s^{-1}$; 5 $m.s^{-1}$ isoline also shown) at 10750m AGL for RURAL-H. The urban region is indicated by the white lines.

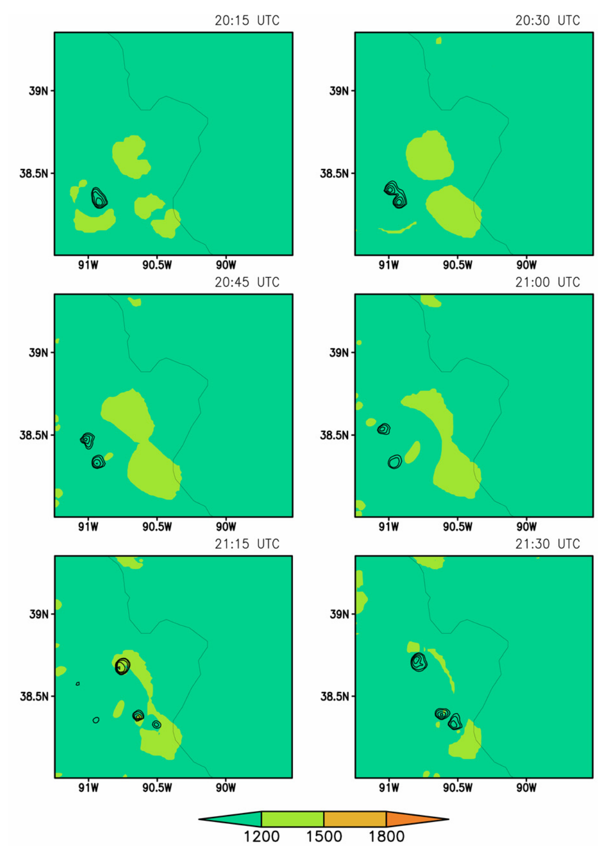

Figure 6: Same as Figure 5 except for NOCITY-H.

Numerous calculations were performed for the region downwind of the city. This region is indicated by the rectangle in Figure 7. Also shown in this figure are the low-level winds and the dispersion of CCN downwind of the city several

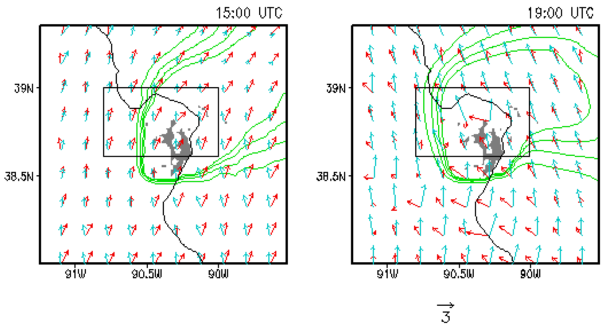

Figure 7: Urban area is indicated by shading. Winds at 1500 UTC (left panel) and 1900 UTC (right panel) at the surface are indicated using the red vectors and those at 1600m AGL using the blue vectors. CCN concentrations at 270m AGL (900, 1000, 1100 and 1200 cc^{-1} isolines shown) are indicated in green.

hours before convective development (1500 UTC) and then for the period just before storm initiation (1900 UTC)

Spatially- and temporally-averaged (2000-2200 UTC) mixing ratios for the downwind region, expressed as a difference between the control simulation (RURAL-H) and the sensitivity test output, are shown in Figure 8. It is apparent from this figure that urban enhancements of CCN concentrations produces the greatest cloud water mixing ratios in the lower levels, while around 5km AGL the cloud water decreases with increasing aerosol concentrations. The averaged rainfall mixing ratios at the surface are greatest, although only slightly, in the case in which GCCN and CCN are enhanced (URBAN-H). Enhanced aerosol concentrations results in pristine ice and snow mixing ratios that are greater than those in the control (RURAL-H) case, except for the GCCN-H simulation around 11 km AGL. A similar result can be seen for the aggregates. Finally, the presence of urban aerosol produces greater graupel and hail mixing ratios compared with the control case.

Comparing the accumulated surface precipitation of the first set of sensitivity tests (Figure 9) as a function of time shows that the enhancement of GCCN or both CCN and GCCN produces greater amounts of surface precipitation than the clean case until around 21:15 UTC, after which the clean case is dominant. The impact of only increasing CCN concentrations results in a reduction in the accumulated surface precipitation.

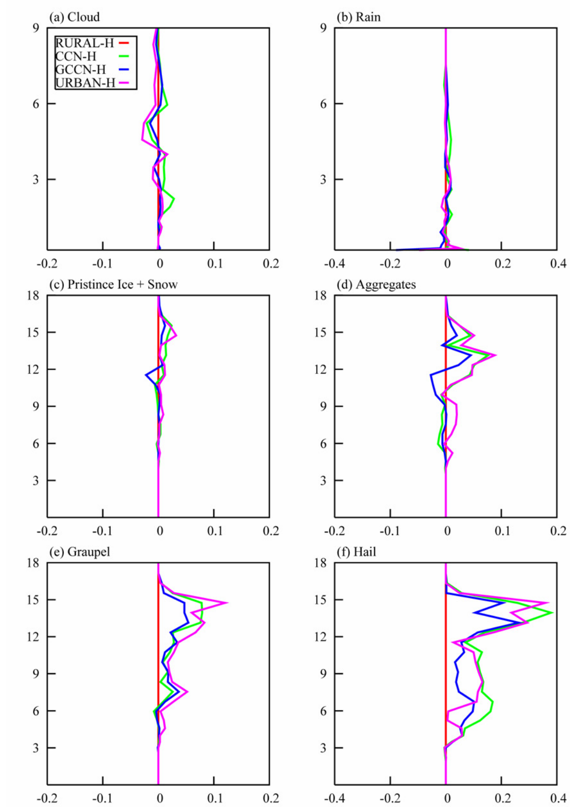

Figure 8: Vertical profiles of the difference between the sensitivity tests and the RURAL-H (CONTROL) simulation for the horizontally (downwind of city) - and temporally (2000-2200 UTC)-averaged cloud water, rain, pristine ice + snow, aggregates, graupel and hail mixing ratios (g/kg) occurring within updraft (> $1 m.s^{-1}$) regions.

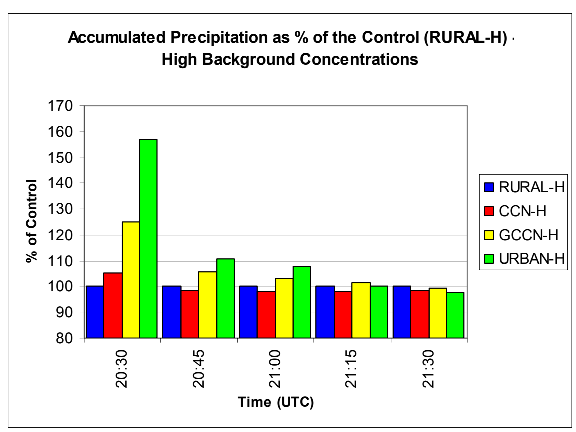

Figure 9: Accumulated surface precipitation as a percentage of the RURAL-H surface precipitation.

While some sensitivity of the hydrometeor mixing ratios and surface precipitation to the aerosol enhancements is observed in these sensitivity tests, the differences from the clean control simulation are relatively small. The background concentrations used for the first set of sensitivity tests is relatively high, although not uncommon for the central regions of the United States (Jim Hudson pers. comm.). In order to investigate the impact that urban-produced aerosols may have on an environment with lower background aerosol concentrations, such as may be found in Canada and Australia for example, another set of sensitivity tests was performed in which lower background CCN and GCCN concentrations were used (Table 1). The results for this set of experiments will now be examined.

Comparing the storm development for the clean control case (with lower background aerosol concentrations) (RURAL-L) (Figure 10) with that in

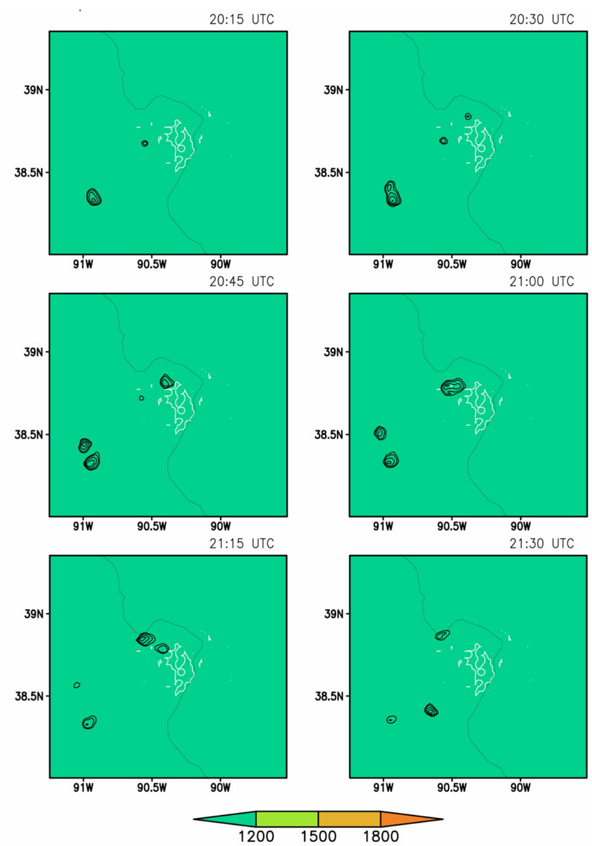

Figure 10: As for Figure 5 except for RURAL-L.

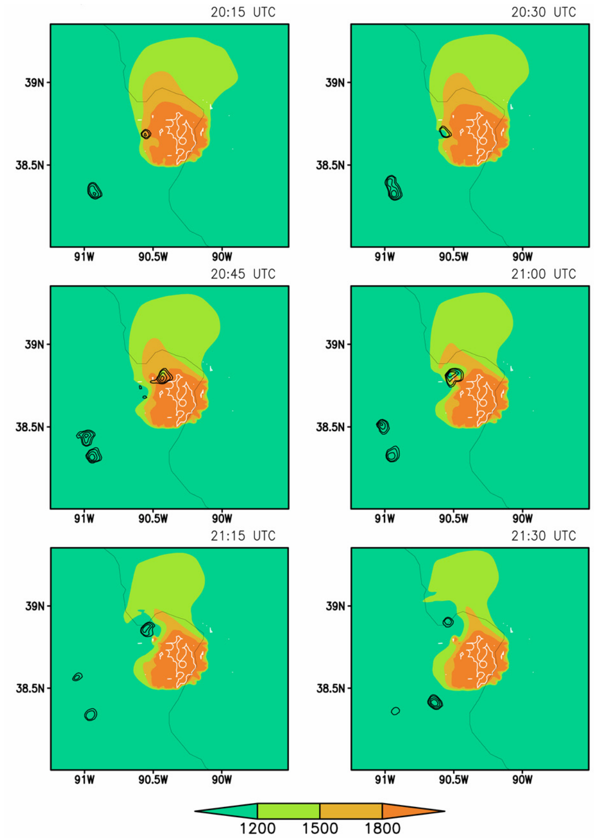

Figure 11: As for Figure 5 except for URBAN-L.

the case in which both CCN and GCCN are enhanced (with lower background aerosol concentrations) (URBAN-L) (Figure 11), several differences are apparent. Storms initiate downwind of the urban region in both cases, however, the number of convective cells that develop and the location of these cells differ. Examining the differences in storm development in the RURAL-L and URBAN-L cases in more detail (Figure 12) shows that the original convective storm appears to split in both cases around 21:00 UTC, however the southern cell, which is closest to the urban regions, rapidly dissipates in the URBAN-L simulation, but is evident in the RURAL-L simulation for another 15 to 20 minutes, and continues to be associated with surface precipitation for another half hour. The presence of urban-enhanced aerosol therefore appears to have a significant effect on the storm dynamics. The factors causing the rapid demise of the southern storm are currently being investigated.

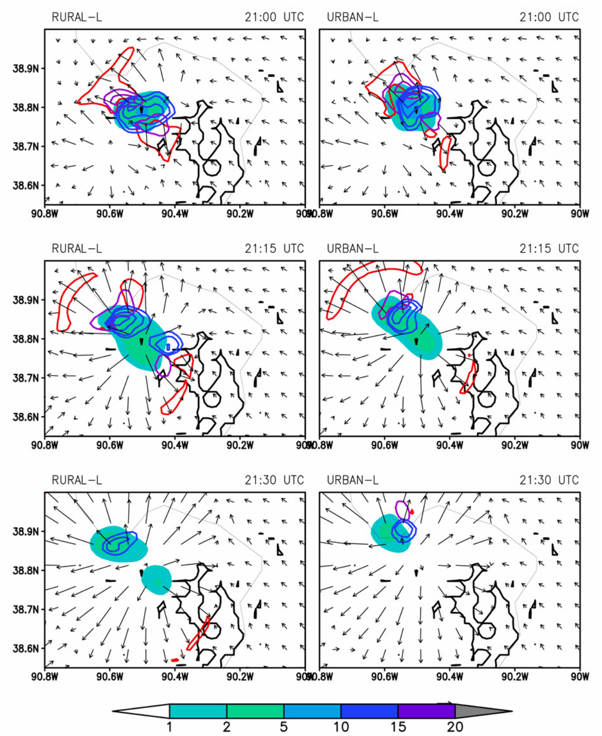

Figure 12: Updrafts at 1350m AGL (red lines), 3015m (purple lines) and 10744m (blue lines) are shown. Contour intervals are 5, 10, 20, 30 m.s^{-1} and the 2 m.s^{-1} isoline is also shown at 1350m. Shading indicates rain mixing ratios (gkg^{-1}) at the surface and wind vectors at the surface are also indicated. The city is indicated with the solid black line.

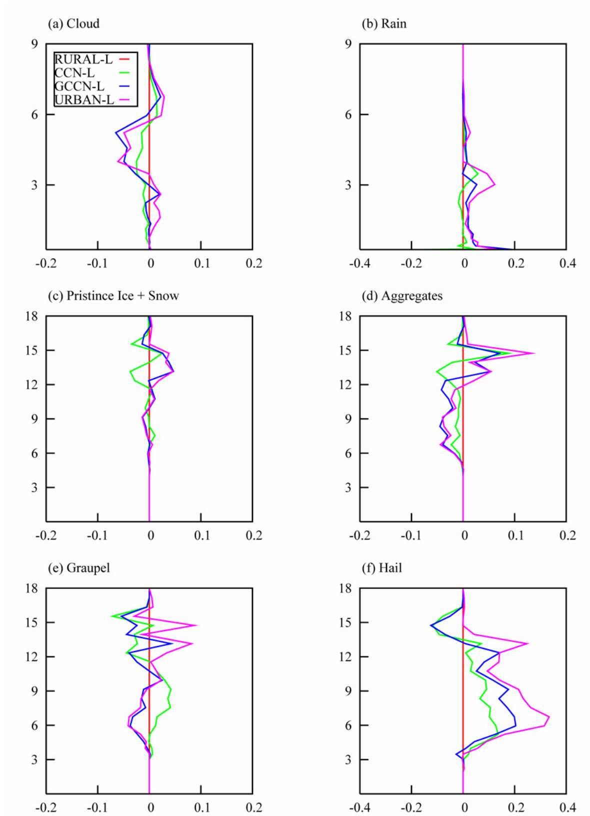

Figure 13: Same as Figure 8 except for the low background aerosol concentration sensitivity tests.

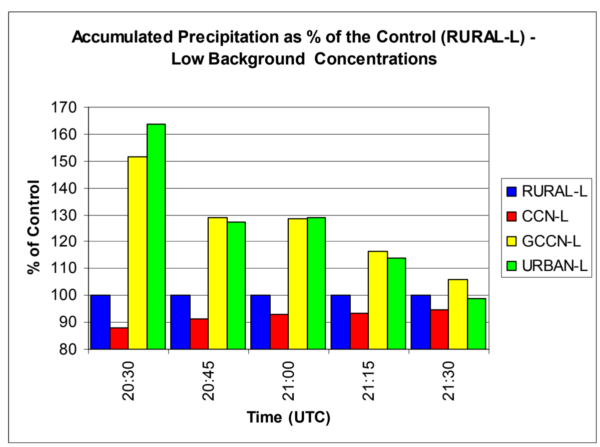

Figure 14: Same as Figure 9 except for the low background aerosol concentrations.

Examining the spatially- and temporally-averaged hydrometeor mixing regions for the downwind region for the low background aerosol concentrations (Figure 13) shows that in the lower levels the URBAN-L case produces the most cloud water, while higher up increasing the aerosol concentrations reduces the cloud water mass, with those sensitivity tests in which GCCN or both CCN and GCCN are enhanced producing the least cloud water. The rain mixing ratios are greatest in the mid-levels and at the surface in the URBAN-L simulation. Pristine ice and snow are more effectively produced when GCCN and both GCCN and CCN concentrations are enhanced, while increasing CCN alone results in a reduction of the mass of these ice species. Aggregate mixing ratios are reduced with increasing aerosol concentrations in the mid-levels, but are enhanced higher up. Graupel mixing ratios are greatest in the upper levels in the URBAN-L case, while enhancements of CCN alone produce more graupel in the lower levels. Finally, increasing CCN, GCCN or both, results in greater hail mixing ratios throughout most of the troposphere, with the URBAN-L case producing the greatest hail mass.

Examining the differences in accumulated surface precipitation for the low background aerosol cases demonstrates that the simulation in which GCCN are exclusively enhanced produces the most surface precipitation, followed by the case in which CCN and GCCN are enhanced (with the exception of 2030 UTC). These differences are on the order of 5 – 50% of the surface precipitation produced in the clean control case. Greater CCN concentrations resulted in a reduction of surface precipitation throughout the simulation.

5. CONCLUSIONS

The urban heat island characteristics, synoptic characteristics and convective storm development are relatively well captured by the simulation. It is apparent from the simulations in which the urban region is excluded that convergence effects of the city have a greater influence than urban aerosol variations on whether or not convective storms develop downwind of the urban region. The presence of urban-enhanced aerosol does however influence the microphysical, dynamical and precipitation characteristics of the storms developing downwind of the city.

It was seen from the sensitivity tests presented above that when the background aerosol concentrations are relatively high, as is the case in the central regions of the United States, the impacts of urban-enhanced aerosol on downwind precipitation, hydrometeor mixing ratios and updraft development are not nearly as significant as when the background aerosol concentrations are lower. Lower background aerosol concentrations are more likely in counties such as Canada and Australia.

It was also seen from the modeling results presented above that the presence of enhanced aerosol concentrations influences the timing, location, splitting and number and strength of updrafts developing downwind of the city. This occurs through latent heat release, precipitation rates and the associated cold pool generation.

For the period in which convective storms are apparent downwind of the city, the simulations in which GCCN are enhanced (GCCN-L, URBAN-L) result in significant increases (15-50% of the control simulation) in the accumulated surface precipitation, although this does decrease toward 2130 UTC. During this same period the enhancement of CCN (CCN-L) associated with the urban region results in a decrease (5-15%) in surface precipitation. Similar trends are also observed during this time period for the high background aerosol simulations however, differences are only of the order of several percent (apart from the initial time). The magnitude of the differences in the hydrometeor mixing ratios was also greater in the sensitivity tests in which the background aerosol concentrations were lower.

The impact of variations in aerosol concentrations not only influences the microphysical and precipitation properties of the convective storms developing downwind of the urban region, but also the storm dynamics. These influences appear to be greater when the aerosol concentrations of the surrounding rural environment are lower.

6. ACKNOWLEDGEMENTS

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