1.4 MODELING DRY AND MOIST CONVECTION FORCED BY AN URBAN HEAT ISLAND

Jong-Jin Baik[1], Yeon-Hee Kim[2], and Hye-Yeong Chun[3]

[1]Seoul National University, [2]Meteorological Research Institute/KMA, [3]Yonsei University, Seoul, Korea

1. INTRODUCTION

Numerous observational studies confirm that cities can initiate convection, split convective storms, change the behavior of convective precipitation, and enhance downstream precipitation. In spite of these evidence, relatively little attention has been paid to providing an explanation of urban-induced weather and climate in a dynamical viewpoint. This study dynamically investigates dry and moist convection forced by an urban heat island through extensive two-dimensional dry and moist simulations.

2. NUMERICAL MODEL

The numerical model used in this study is the Advanced Regional Prediction System (ARPS), which is a nonhydrostatic, compressible, finite-difference model with complete physical parameterizations (Xue et al. 1995). The urban heat island is represented by specified heating and the basic-state wind is set to be uniform in the vertical. In moist simulations, the mixing ratios of water vapor, cloud water, and rainwater are explicitly predicted with a bulk cloud microphysical parameterization scheme. The physical domain sizes are 150 km in the horizontal and 12 km in the vertical. The horizontal and vertical grid intervals are 1 km and 150 m, respectively. To minimize the reflection of gravity waves at boundaries, a radiation boundary condition is employed at lateral boundaries and a sponge layer is put from z = 12 to 15 km, with height-dependent damping coefficients. With a large time step of 4 s and a small time step of 1 s (terms associated with acoustic waves), the model is integrated for 6 hours.

3. RESULTS

Extensive numerical experiments with various heating amplitudes, representing the intensity of the urban heat island, uniform basic-state wind speeds, and basic-state relative humidities are performed to examine their roles in characterizing urban-induced convection (40 dry and 100 moist simulations).

Two flow regimes are identified in dry simulations. One regime is characterized only by stationary gravity waves near the heating region and is revealed when the urban heat island intensity is very weak. The other regime is characterized both by stationary gravity waves near the heating region and by a downwind updraft cell that moves in the downstream direction. The intensity of the downwind updraft cell increases as the heat island intensity increases or the basic-state wind speed decreases.

Figure 1 shows the cloud water mixing ratio fields at t = 2, 3, and 4 h in the case of q_0 (heating amplitude) = 1.2 J kg^{-1} s^{-1}, U (basic-state wind speed) = 5 m s^{-1}, and RH$_L$ (boundary-layer relative humidity) = 90%. In this case, the calculated convective available potential energy (CAPE) for the basic-state thermodynamic soundings is 101 J kg^{-1} when the moisture effect is taken into account. Cloud water is produced for the first time as a result of the condensation of water vapor at x = 63 km and t = 63 min. Note that the center of the urban heat island is located at x = 50 km. At this time, the center of the downwind updraft cell induced by the heating is located at x = 63 km and its maximum intensity is 0.36 m s^{-1}. Therefore, the horizontal location of cloud formation coincides with that of the center of the downwind updraft cell. This implies that the updraft cell moving downstream initiated moist convection downstream. Before the cloud forms, the vertical velocity field in the moist simulation is very similar to that in the corresponding dry simulation case because there is no latent heat release yet from the condensation of water vapor.

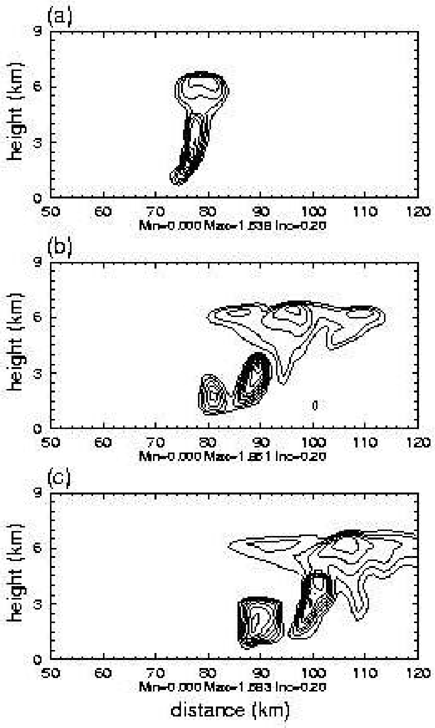

Figure 1. The fields of cloud water mixing ratio at t = (a) 2, (b) 3, and (c) 4 h in a moist simulation with q_0 = 1.2 J kg^{-1} s^{-1}, U = 5 m s^{-1}, and RH$_L$ = 90%. The min and max values and the contour interval (inc) are shown at the bottom of each frame (g kg^{-1}).

Corresponding author address: Jong-Jin Baik, School of Earth and Environmental Sciences, Seoul National University, Seoul 151-742, Korea.
e-mail:jjbaik@snu.ac.kr

Figure 2 depicts the time and horizontal location at which cloud water and rainwater are first produced as a function of heating amplitude in simulations with U = 5 m s^{-1} and RH$_L$ = 90%. Figure 2a indicates that as the heating amplitude increases, the time required for the first cloud water formation decreases. The variation in the time of the first cloud water formation is more sensitive to small heating amplitude than to large heating amplitude. These results are also true for the rainwater formation. Some time after cloud water forms, autoconversion process starts that initiates rainwater when the cloud water mixing ratio exceeds a critical value (1 g kg^{-1}). The time required from the first cloud water formation to the first rainwater formation becomes shorter as the heating amplitude becomes larger. It takes 31 min in the q_0 = 1 J kg^{-1} s^{-1} case, but it takes only 14 min in the q_0 = 2 J kg^{-1} s^{-1} case.

Figure 2b reveals that the horizontal location of the first cloud water formation is farther away from the heating center (x = 50 km) as the heating amplitude decreases. The variation in the horizontal location of the first cloud water formation is more sensitive to small heating amplitude than to large heating amplitude. The horizontal location of the first rainwater formation follows the same patterns. The distance between the horizontal location of the first cloud water formation and that of the first rainwater formation decreases as the heating amplitude increases. The distances are 7 and 3 km in the q_0 = 1 and 2 J kg^{-1} s^{-1}, respectively.

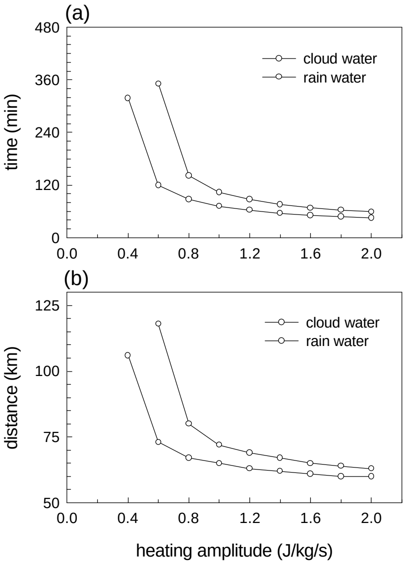

Figure 2. (a) Time and (b) horizontal location at which cloud water and rainwater are first produced as a function of heating amplitude in moist simulations with U = 5 m s^{-1} and RH$_L$ = 90%.

4. DISCUSSION

The results of extensive moist simulations suggest that the downwind updraft cell that is thermally induced by the urban heat island can trigger moist convection and thus result in precipitation in the downstream region if certain environmental conditions necessary to support moist convection are met. The urban heat island-induced downwind updraft cell is a dynamic trigger for moist convection. This mechanism can explain the precipitation enhancement observed downwind of urban areas. However, this result should not be interpreted in a way that assigns the urban heat island as a primary cause of downstream precipitation enhancement in all observational cases. There can be observational cases in which the urban heat island is not a dominant cause. The urban heat island in itself implies a spatial variation in temperature between the urban area and its surroundings. Therefore, there always exists a possibility that downstream moist convection and precipitation can take place because of an urban heat island-induced updraft cell if urban heat island intensity is strong and environmental conditions become favorable.

In this study, in order to isolate the role of the urban heat island in urban-induced convection and precipitation, other potential factors were not considered. One of these is the difference in land use between urban area and its surroundings. In particular, changes in surface roughness can change or modify atmospheric circulation and hence the behavior of convection and precipitation. This needs to be systematically investigated in isolation from and then in connection with urban heat island-induced circulation. In this study, a stable basic-state thermal structure was set in every case. The nocturnal urban heat island generally develops in a stable boundary layer and its intensity is known to be stronger than that of the daytime heat island. The daytime urban heat island, on the other hand, can develop in a nearly neutral boundary layer. This difference in the boundary-layer thermal stability can significantly influence heat island circulation. The effects of atmospheric thermal stability on urban heat island-induced convection and precipitation deserve in-depth investigation. It is hoped that the current study or similar kinds of studies can provide some valuable dynamical insight for a more through understanding of urban-induced weather and climate in complex real situations. For further details, see Baik (1992) and Baik et al. (2001).

5. ACKNOWLEDGMENTS

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