3.6 A THEORETICAL AND NUMERICAL STUDY OF URBAN HEAT ISLAND-INDUCED CIRCULATION AND CONVECTION

Ji-Young Han and Jong-Jin Baik *
School of Earth and Environmental Sciences, Seoul National University, Seoul, Korea

1. INTRODUCTION

Numerous observational studies have shown that the frequency of cloud occurrence and lighting is increased and precipitation is enhanced downstream of urban areas. Using a two-dimensional numerical model, Baik et al. (2001) showed that urban heat island-induced updraft cell moving downstream can initiate moist convection and result in downwind precipitation under favorable thermodynamic conditions. This study extends our previous one (Baik et al. 2001) and investigates urban heat island-induced circulation and convection in three dimensions theoretically and numerically in the context of the response of a stably stratified uniform flow to specified low-level heating.

2. THEORETICAL APPROACH

Most of previous linear studies considered two-dimensional airflow system to simplify the problem mathematically. However, in an effort to better understand urban heat island-induced circulation, it is more appropriate to consider three-dimensional airflow system. In this study, analytic solutions in physical space for the equations governing small-amplitude perturbations in a three-dimensional, time-dependent, hydrostatic, nonrotating, inviscid, and Boussinesq airflow system are obtained using the Green's function method. Specified low-level heating that represents an urban heat island is bell-shaped in the horizontal and decreases exponentially with height.

The solutions reveal typical internal gravity-wave fields in response to the thermal forcing. These include upstream phase tilt of the perturbation fields, implying upward wave energy propagation, and low-level upward motion downstream of the thermal forcing. Precipitation enhancement downwind of the urban heat island may be partly due to this downstream upward motion.

Figure 1 shows the perturbation vertical velocity fields at t = 10 h in (a) two and (b) three dimensions. The flow response pattern in three dimensions is similar to that in two dimensions, but there are some differences between them. The stationary gravity wave field near the heating region and the maximum perturbation vertical velocity in the quasi-steady state are weaker in three dimensions because of the dispersion of gravity-wave energy into an additional dimension. Compensating downward motion in three dimensions is also weaker than that in two dimensions, since there is no compensating downward motion in the y-direction in two dimensions. The tilting slope of upstream phase is larger in three dimensions because the horizontal decay rate of specified low-level heating in three dimensions is larger than that in two dimensions. This can be confirmed by the fact that as y-directional distance from the heating center increases, that is, horizontal decay rate near the heating center decreases, the tilting slope of upstream phase decreases. Note that in a theoretical study, low-level heating in two and three dimensions are assumed to have different horizontal decay rate for mathematical reason ($q_{2D} \propto [(x/a_x)^2+1]^{-1}$, $q_{3D} \propto [(x/a_x)^2+(y/a_y)^2+1]^{-3/2}$).

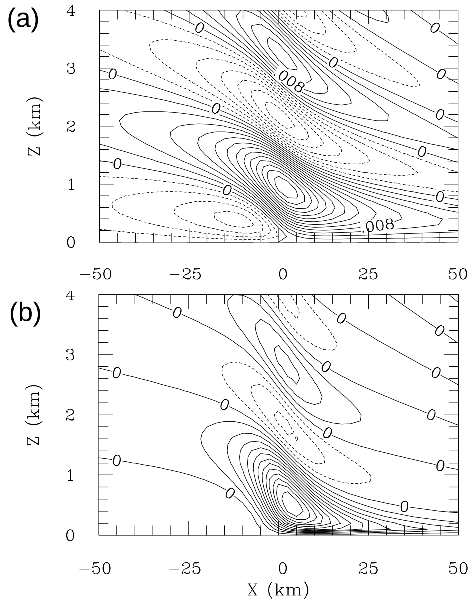

Figure 1. The perturbation vertical velocity fields at t = 10 h in (a) two and (b) three dimensions (along y = 0) with q_0 = 0.1 J kg^{-1} s^{-1}, N = 0.01 s^{-1}, T_0 = 288 K, U = 3.5 m s^{-1}, V = 0 m s^{-1}, $a_x = a_y$ = 10 km, and h = 700 m. The heating center is located at x = 0 km (and y = 0 km). The contour interval is 0.002 m s^{-1}.

3. NUMERICAL APPROACH

3.1 *Numerical Model and Experimental Design*

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* *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

The numerical model used in this study is the Advanced Regional Prediction System (ARPS), which is a three-dimensional, nonhydrostatic, compressible model with advanced physical parameterizations (Xue et al. 1995). To isolate urban heat island effects on urban-induced precipitation changes, other potential factors such as surface roughness are not considered. Surface, radiation and ice-phase cloud microphysical processes and the rotational effect of the earth are neglected. In moist simulations, warm-cloud bulk parameterization scheme is used.

The vertical profile of the basic-state temperature follows that of the standard atmosphere. The basic-state relative humidity is constant with 90% from the surface to z = 1 km, decreases linearly with height up to z = 11 km, and is constant above with 10%. This thermodynamic sounding has a convective available potential energy (CAPE) of 101 J kg^{-1} when the moisture effect is included. The model domain sizes are 150 x 100 x 15 km. The horizontal and vertical grid sizes are 1 km and 150 m, respectively. To prevent wave reflection at boundaries, the lateral radiation boundary condition is used and the damping layer is located from z = 12 km to model top height. The model is integrated up to 6 h with a large time step of 2 s and a small time step related to acoustic waves of 0.5 s. Specified low-level heating is the same as that of theoretical study.

3.2 *Results and Discussion*

Extensive dry and moist simulations with various heating amplitudes and uniform basic-state wind speeds are performed to investigate urban heat island-induced convection and precipitation.

Results in three dimensions are compared with our previous results in two dimensions (Baik et al. 2001). In dry simulations, as the heating amplitude increases or the basic-state wind speed decreases, that is, nonlinearity increases, the flow response fields gradually deviate from the linear internal gravity wave fields in both two and three dimensions. However, unlike two-dimensional dry simulations, in which the well-organized downwind updraft cell is separated from the stationary gravity wave field near the heating region and propagates downstream continuously, in three-dimensional dry simulations, such separation does not occur and the location of the maximum updraft becomes quasi-stationary for all basic-state wind speeds (Fig. 2).

As a three-dimensional heat source is elongated in the y-direction, that is, the y-directional structure of the low-level heating in three dimensions approaches that in two dimensions, downwind updraft cell separated from the stationary gravity wave field appears and continues to move downstream. This result indicates that the horizontal structure of the urban heat island can significantly influence atmospheric circulation and hence the behavior of convection and precipitation.

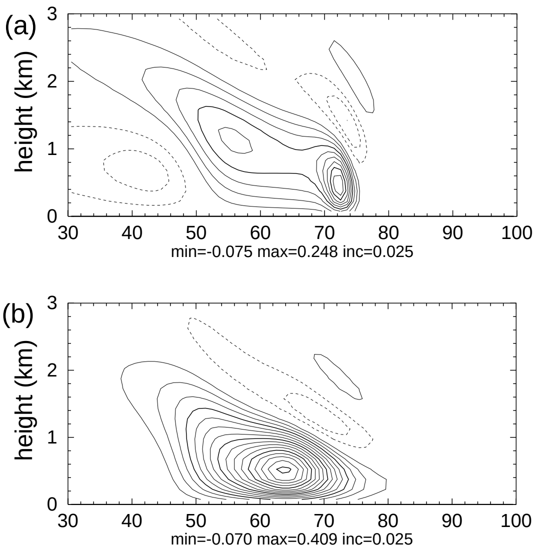

Figure 2. The perturbation vertical velocity fields at t = 3 h in (a) two and (b) three dimensions (along y = 50 km) with q_0 = 0.8 J kg^{-1} s^{-1}, U = 4 m s^{-1}, V = 0 m s^{-1}, a_x = a_y = 10 km, and h = 700 m. The heating center is located at x = 50 km (and y = 50 km). Zero-contour lines are not drawn. The min and max values and the contour interval (inc) are shown at the bottom of each frame (m s^{-1}).

Results of moist simulations demonstrated that downwind upward motion induced by the urban heat island can initiate moist convection and result in downwind precipitation under favorable thermodynamic conditions. The first cloud water and rainwater formation in three-dimensional moist simulations occur earlier and closer to the heating center than those in two-dimensional moist simulations, since the maximum downwind updraft in three dimensions develops more rapidly at the early stage. Precipitation pattern in three dimensions is also different from that in two dimensions. In three dimensions, localized heavy rainfall occurs not far from the heating center by the convective precipitating cloud that is nearly stationary. However, in two dimensions, the amount of the surface precipitation is dramatically reduced and its area farther away from the heating center becomes wider.

Our numerical modeling results highlight a universal role that the urban heat island plays in downwind precipitation enhancement. The current study will be extended to examine to what extent increased surface roughness contributes to urban-induced convection and precipitation.

4. REFERENCES

Baik, J.-J., Y.-H. Kim, and H.-Y. Chun, 2001: Dry and moist convection forced by an urban heat island. *J. Appl. Meteor.*, **40**, 1462-1475.

Xue, M., K. K. Droegemeier, V. Wong, A. Shapiro, and K. Brewster, 1995: ARPS version 4.0 User's Guide. CAPS, University of Oklahoma, 380 pp.