

Effects of building–roof cooling on the flow and dispersion of reactive pollutants in an idealized urban street canyon

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ABSTRACT

This study investigated the characteristics of the flow and dispersion of reactive pollutants in three-dimensional idealized street canyons in the presence of building-roof cooling to provide implications in how a green-roof system contributes to mitigating of pedestrian exposure to near-roadway air pollution in street canyons. The pollutant chemistry was simulated using a coupled CFD-chemistry model. In the presence of building-roof cooling, winds and temperature fields inside the building canopy of the street canyon were significantly modified. Building-roof cooling, intensified the street-canyon vortex strength (up to 26.6% in downdraft, 10.4% reverse flow, and 7.7% in updraft). Building-roof cooling also decreased air temperature in the street canyon by supplying cooler air near the building roof. The changes in the in-canopy distributions of primary pollutants (NO_x, VOCs and CO) due to building-roof cooling were mainly caused by the modified mean flow rather than the chemical reactions. High concentrations of primary pollutants occurred near the upwind building because the reverse flows were dominant at street level, making this area the downwind region of emission sources. Ozone concentrations were lower than the background concentration near the ground, where NO_x concentrations were high. Building-roof cooling decreased primary pollutant concentrations by approximately −2.4% compared to those under non-cooling conditions. By contrast, building-roof cooling increased O₃ concentrations by about 1.1% by reducing NO concentrations in the street canyon compared to concentrations under non-cooling conditions.

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1. Introduction

Land use changes in expanding urban areas affect the thermal environment by altering the surface radiation and energy budget [1,2]. The reduction of vegetated areas and the expansion of paved areas increase the energy storage in urban areas [3,4], creating unpleasant conditions and leading to adverse human health effects, particularly during hot weather [5].

Many studies [6–8] have investigated the effect of vegetated roofs on mitigating the urban heat island phenomenon. Alexandri and Jones [6] found that the air temperature decreased in hot, dry, and humid weather in urban areas where building walls and roofs

were covered with vegetation. The effects of both wall- and roof-cooling due to vegetation were more effective in hotter and drier conditions.

The thermal environment affects the flow and dispersion of pollutants in street canyons [9–12]. Sini et al. [9] and Li et al. [12] showed that the differential heating of wall or ground surfaces modified the flow structure/intensities and the corresponding ventilation of pollutants. Based on both observations and a model simulation, Offerle et al. [10] showed that the surface (wall) heating influences wind speed, wind direction, and air temperature in urban street canyons.

With regard to in-canyon air quality, most studies have focused on the dispersion of nonreactive pollutants [13,14]. However, vehicular emissions, a major pollution source in urban areas, consist mostly of reactive pollutants, such as nitrogen oxides (NO_x = NO + NO₂) and volatile organic compounds (VOCs). Toxic secondary pollutants, such as ozone (O₃), are produced in the

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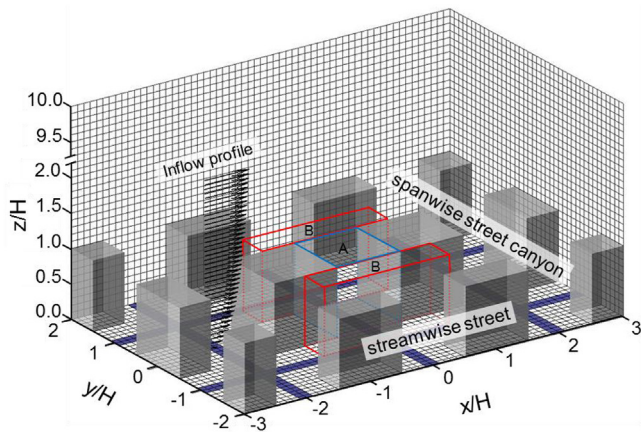


Fig. 1. Computational domain and building configuration. The blue color indicates emission sources. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

atmosphere chemically [15]. To simulate the dispersion of reactive pollutants, some studies have considered chemical reactions in their model simulations. Kang et al. [16] examined the diurnal variation of NO_x and O_3 in an urban street canyon for different intensities of ground-surface heating using the steady-state O_3 - NO - NO_2 photochemistry. Kwak et al. [17] presented the effects of VOCs and NO_x emission ratios on their distributions in street canyons using a computational fluid dynamics (CFD) model coupled with the carbon bond mechanism IV (CBM-IV). However, the distributions of the reactive pollutants were not discussed in detail. Park et al. [18] analyzed in detail the effects of street canyon aspect ratios and VOCs- NO_x ratios on the distributions of reactive pollutants using a coupled CFD-chemistry model, but building-roof cooling effects were not considered. Most studies have investigated scalar pollutants in a 2-dimensional street canyon and few studies have simulated building-roof cooling. Investigating the characteristics of flow and the dispersion of pollutants in idealized street canyons can help better understand the microscale air quality associated with complicated meteorological phenomena in real urban areas. However, few studies have investigated the effects of the thermal environment modified by vegetated surfaces on flow dynamics as well as the dispersion of reactive pollutants. Therefore, this study quantified the effects of building-roof cooling on the flow and dispersion of reactive pollutants in a fluid dynamics and pollutant chemistry framework, applying a coupled CFD-chemistry model to three-dimensional idealized street canyons. This study provides implications in how the green-roof system contributes to mitigating pedestrian exposure to near-roadway air pollution in street canyons. The remainder of this paper is structured as follows. Section 2 describes the model, simulation setup, model validation. Section 3 describes the simulation results in detail and includes schematic diagrams inform a dynamics perspective. Finally, we summarize and conclude our findings.

Table 1
Boundary conditions applied in this simulation.

	Flow	Dispersion
Solid wall	Wall function	Dirichlet condition
Inflow	Unchanged with time	Periodic condition
Outflow	Zero-gradient condition	Zero-gradient condition
Lateral boundary	Zero-gradient condition	Zero-gradient condition

Table 2

Summary of building-roof cooling scenarios (air and building wall temperatures are fixed at 20 °C and ground temperature at 50 °C).

Experiment	CNTL	EXP1	EXP2	EXP3	EXP4	EXP5	EXP6
Building-roof temperature	50 °C	45 °C	40 °C	35 °C	30 °C	25 °C	20 °C

2. Model description and simulation setup

2.1. Model description

The coupled CFD-chemistry model used in this study is the same as that used in Kim et al. [19] and Park et al. [18]. A full tropospheric NO_x - O_x -VOC chemical mechanism from the Goddard Earth Observing System (GEOS)-Chem [20] was coupled with the CFD model in Kim and Baik [11]. The CFD model assumes a three-dimensional, non-hydrostatic, non-rotating, and Boussinesq air flow system. The governing equations are numerically solved using finite volume and semi-implicit methods for a pressure-linked equation (Semi-Implicit Method for Pressure-Linked Equations; SIMPLE) algorithm [21]. In the SIMPLE algorithm, three wind components are calculated first under an assumed pressure deviation field. The pressure and wind-component deviations are calculated using the pressure-linked equations. At each time step, this procedure is repeated until the adjusted solutions attain the desired accuracy. This model employs a k - ϵ turbulence closure scheme based on renormalization group (RNG) theory. To consider the wall boundary effects, the wall functions for momentum, heat, turbulent kinetic energy (TKE), and TKE dissipation rates proposed by Versteeg and Malalasekera [21] are used in the CFD model. For details of the CFD model, see Refs. [11,13]. GEOS-Chem includes 343 chemical reactions for 110 species, including 50 photochemical reactions. The chemical reactions were solved using a gear type solver (Sparse Matrix Vectorized Gear Code; SMVGEAR) [22], and for photolysis rates, the Fast-J algorithm developed by Wild et al. [23] was implemented.

2.2. Simulation setup

To investigate the effects of building-roof cooling on the flow and dispersion of reactive pollutants in street canyons, we adopted the same computational domain, grid system, and boundary conditions used in Park et al. [18] and fixed the building height (H) at 20 m (Fig. 1). The domain sizes (cell numbers) were $120 \times 80 \times 200$ m ($60 \times 40 \times 100$) in the x -, y -, and z -directions, respectively. The grid intervals were 2 m in all directions. The building width (W), building length (L), and street width (S) were also fixed at 20 m, consequently, all building and/or street aspect ratios defined as H/S , W/L , W/S , and L/S are unity. The spaces between the buildings in the x - and y -directions were referred to as the streamwise and spanwise street canyons, respectively. The initial profiles for wind (U , V , W), air temperature (T), TKE (k), and the TKE dissipation rate (ϵ) were determined as follows [24]:

$$U(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right), \quad (1)$$

$$V(z) = 0, \quad (2)$$

$$W(z) = 0, \quad (3)$$

$$T(z) = 20^\circ\text{C}, \quad (4)$$

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