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The impacts of building height variations and building packing densities on flow adjustment and city breathability in idealized urban models

Lan Chen [a], Jian Hang [a, b, *], Mats Sandberg [c], Leif Claesson [c], Silvana Di Sabatino [d], Hans Wigo [c]

[a] School of Atmospheric Sciences, Sun Yat-sen University, Guangzhou, PR China
[b] Institute of Earth Climate and Environment System, Sun Yat-sen University, Guangzhou, PR China
[c] Laboratory of Ventilation and Air Quality, University of Gävle, SE-80176 Gävle, Sweden
[d] Department of Physics and Astronomy - DIFA, ALMA MATER STUDIORUM - University of Bologna, Viale Berti Pichat 6/2, 40127 Bologna, Italy

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ABSTRACT

Improving city breathability has been confirmed as one feasible measure to improve pollutant dilution in the urban canopy layer (UCL). Building height variability enhances vertical mixing, but its impacts remain not completely explored. Therefore, both wind tunnel experiments and computational fluid dynamic (CFD) simulations are used to investigate the effect of building height variations (six height standard deviations $\sigma_H = 0\%-77.8\%$) associated to building packing densities namely $\lambda_p/\lambda_f = 0.25/0.375$ (medium-density) and 0.44/0.67 (compact) on city breathability. Two bulk variables (i.e. the in-canopy velocity (U_C) and exchange velocity (U_E)) are adopted to quantify the horizontal and vertical city breathability respectively, which are normalized by the reference velocity (U_{ref}) in the free flow, typically set at $z = 2.5H_0$ where H_0 is the mean building height.

Both flow quantities and city breathability experience a flow adjustment process, then reach a balance. The adjustment distance is at least three times longer than four rows documented in previous literature. The medium-density arrays experience much larger U_C and U_E than the compact ones. U_E is found mainly induced by vertical turbulent fluxes, instead of vertical mean flows. In height-variation cases, taller buildings experience larger drag force and city breathability than lower buildings and those in uniform-height cases. For medium-density and compact models with uniform height, the balanced U_C/U_{ref} are 0.124 and 0.105 respectively, moreover the balanced U_E/U_{ref} are 0.0078 and 0.0065. In contrast, the average U_C/U_{ref} in height-variation cases are larger (115.3%–139.5% and 125.7%–141.9% of uniform-height cases) but U_E/U_{ref} are smaller (74.4%–79.5% and 61.5%–86.2% of uniform-height cases) for medium-density and compact models.

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1. Introduction

In 2011, about 3.5 billion (51%) of world population lived in cities, and this number is predicted to reach about 5.0 billion (60%) by 2030 [1]. The ongoing urbanization worldwide and the increasing vehicle emissions in cities have raised much environmental concern on urban air pollution and its adverse effects on public health [2–4]. Urbanization is also responsible for the exacerbation of the urban heat island phenomenon generating concern about the increasing of urban energy consumption for summertime cooling [5,6] in many cities in the world.

From the physical view of the urban canopy layer (UCL), where people live and where the emission sources are, is defined as the layer of the atmosphere from the ground to the rooftop of buildings in urban regions (Fig. 1a). Improving ventilation within UCL has been confirmed one of the effective technique in helping pollutant and heat dilution [7–14].

In the last three decades, as reviewed by the literature [15–21] a number of outdoor field measurements, computational fluid dynamic (CFD) simulations and controlled laboratory experiments

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* Corresponding author. School of Atmospheric Sciences, Sun Yat-sen University, Guangzhou, PR China.
E-mail address: hangj3@mail.sysu.edu.cn (J. Hang).

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have been carried out for urban airflow and dispersion modeling within and above UCL models in street-scale (~100 m) and neighborhood-scale (~1 km). Urban morphologies and meteorological conditions are key parameters for UCL ventilation, such as street aspect ratios (building height/street width, H/W) [22–24], building packing densities (Fig. 1b) [25–28], ambient wind directions [11,29–32,36], building height variations [33–36], urban tree planting [37,38], the buoyancy force induced by wall heating and solar radiation shading [39–47] etc.

City breathability was first defined by Neophytou and Britter [48,49] as a UCL ventilation concept reflecting a city's potential to dilute and remove pollutants, heat, moisture, and other scalars. Nevertheless, the initial concept was not quantified in terms of specific variables which was later done in Buccolieri et al. [27] where the concept of age of air was used to explain pollution hot spots in arrays of buildings. As displayed in Fig. 1a, the starting point of city breathability is the assumption that the surrounding air is relatively clean, and the air exchange between the external flow and the in-canopy flow contributes to supplying clean air into cities (inhale effect) and removing pollutants out (exhale effect). The capacity of city breathability is associated with the interaction between the approaching atmospheric flow and urban morphologies.

In recent years, city breathability and their correlation with urban morphologies have been accessed and quantified by some ventilation indices such as volumetric flow rate and air change rate per hour [24,25,29,30,32], purging flow rate and pollutant retention time [10,34], age of air and ventilation efficiency [25–27,29], net escape velocity [36], exchange velocity and in-canopy velocity [48–53] etc. Horizontal mean flows, vertical mean flows and vertical turbulent diffusions are verified to make significant contribution on city breathability. Specially, as first originated by Bentham and Britter [48], the concept of in-canopy velocity (U_C) represents a constant velocity within the urban canopy layer to quantify the scale of horizontal dilution capacity instead of a velocity profile in street canyons (Fig. 1c). Moreover, the concept of exchange velocity (U_E) represents the average velocity of scalar transfer out of or into the UCL at an interface plane (i.e. roof level) between the in-canopy and above-canopy flows (Fig. 1c). Here U_E can be used to evaluate overall vertical ventilation performance induced by vertical mean flows and vertical turbulent diffusion. Later U_E and U_C were introduced into CFD simulations to successfully estimate the city breathability induced by vertical exchange (U_E) and horizontal dilution (U_C) respectively in idealized UCL models [50–52] or realistic urban areas [49,53].

In addition, there are two groups in urban flow and dispersion modeling. One group considers the flow adjustment from the upstream toward downstream regions and resolves the airflows around all buildings in the target urban domain in which the effects of urban boundaries are considered [9–11,23–30,34–36]. As defined by Belcher et al. [54] (Fig. 1a), the “adjustment region” is downwind of the windward UCL boundaries and below UCL rooftop where the horizontal flow substantially decelerates and a fraction of air is driven out upwardly across UCL roofs (i.e. exchange velocity U_E and in-canopy velocity U_C change toward downstream urban regions). Then it comes into the “canopy interior” region [54] or the “fully-developed region” [32], where a local flow balance is established between downward transport of momentum by turbulent stresses and removal of momentum by the drag of the canopy elements (i.e. U_E and U_C keep constants). The other group only considers a periodic urban unit in the “canopy interior” region assuming the UCL model is infinitely large and uniform to apply periodic boundaries for one unit [31–33]. This paper aims to investigate the effects of building height variations on the adjustment of both urban airflow and city breathability (U_E and U_C).

As first defined by Grimmond and Oke [55] (Fig. 1b), the building planar area index λ_p (i.e. the ratio between the planar area of buildings viewed from above and the total floor area) and the frontal area index λ_f (i.e. the ratio of the frontal area of buildings to the total floor area) are usually adopted to quantify urban compactness. Sparse UCL models (i.e. $\lambda_f = 0.0625$ or 0.11) usually attain better city breathability, but have a low efficiency of land utilization. Densely built-up urban areas (i.e. $\lambda_f = 0.56$ or more) experience a higher land-use efficiency but come into a challenge in inducing worse UCL ventilation [25–28,56–58]. The typical medium and compact UCL models are usually reported as $\lambda_p = 0.25$ or 0.44 [25–28,56–58]. In addition, building height variations can significantly influence city breathability [33–36]. In this context, the main objective of the paper is to examine the influence of typical building height variations and building packing densities ($\lambda_p = 0.25$ or 0.44, average $\lambda_f = 0.375$ or 0.67) on city breathability (U_E and U_C) and their adjustment processes, which have been rarely investigated.

The remainder of this paper is structured as below: Section 2 describes the CFD methodologies and wind tunnel studies, including the concepts of in-canopy velocity (U_C) and exchange velocity (U_E) (subsection 2.1), the setups of wind tunnel experiments (subsection 2.2) and numerical models (subsection 2.3). Section 3 presents the CFD validation using wind tunnel data. Results are discussed in Section 4 and conclusions are drawn in Section 5.

2. CFD methodologies and wind tunnel studies

2.1. Concepts of in-canopy velocity (U_C) and exchange velocity (U_E)

On the assumption that the in-canopy flow below roof level follows a constant velocity rather than the usual logarithmic profile, Bentham and Britter [48] firstly deduced the spatially and temporally simplified in-canopy velocity (U_C). Results for U_C were evaluated by a number of wind tunnel data and were found in good agreement.

As presented in Eq. (1), the scale of U_C is determined by the pressure force (F_p) acting on the building and the drag coefficient (C_D). F_p can be calculated by the net pressure surface integral on the frontal and back area of the building unit. C_D is assigned a standard value of 1 [50], and A_f refers to the building's frontal area.

$$U_C = \sqrt{\frac{2F_P}{\rho C_D A_f}} \tag{1}$$

The exchange velocity (U_E) was derived for the vertical exchange rate, of pollutant, heat or water vapor being removed or added at the top of the urban canopy layer [48]. The exchange velocity (U_E) is also relevant to determine the vertical momentum transport to the urban canopy layer, which counterbalances the form drag induced by buildings. Hamlyn and Britter [50] first applied U_E into CFD simulations to quantify the city breathability in idealized building clusters. It is defined as a ratio of the momentum flux to the difference between the mass flux above and below the UCL top (i.e. the exchange plane (A_c) in Fig. 1c).

$$U_E = \frac{\iint \left(\rho \overline{u'w'} + \rho \overline{u}\overline{w} \right) dS}{\rho A_C \left(U_{\text{ref}} - U_C \right)} \tag{2}$$

The vertical momentum flux in Eq. (2) is produced by two terms, one is evaluated from the vertical Reynolds' shear stress ($\rho \overline{u'w'}$) and the other is the vertical flux induced by vertical mean flows

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