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Street-canyon pollution with respect to urban-array complexity: The role of lateral and mean pollution fluxes

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ABSTRACT

The prediction of pollution within street canyons remains challenging due to the complexity of turbulent flows in urban environments. To improve our understanding of these flows and their relation to the ventilation of street-canyons, we studied pollution fluxes through all street-canyon openings and their balance with respect to urban-array complexity using large-eddy simulations (LES). We validated the LES with wind-tunnel measurements using mean velocities and concentrations and the mean total and turbulent pollution fluxes at the top and lateral openings of the street canyons with either uniform or nonuniform heights and pitched roofs. The LES confirm and extend recent findings about the importance of mean horizontal pollution fluxes for pollutant transport within a street network. The mean fluxes have at least the same dominance as the turbulent ones in case of lateral openings. In case of top openings, the mean fluxes clearly dominate if openings at the roof eaves are selected. While pollutant removal and entrainment through lateral openings are negligible in case of uniform canyons, they are notable in case of nonuniform canyons. We demonstrate that urban roof height nonuniformity does not necessarily enhance the street-canyon ventilation because it worsens (by a factor of 1.1) or improves (by a factor of 1.5) the ventilation compared with the urban uniform height.

1. Introduction

Approximately 4.1 million premature deaths in 2016 are attributable to ambient air pollution [1]. Due to traffic and the building geometry, urban street canyons are one of the most polluted places in the world. Therefore, the assessment and prediction of street-canyon pollution is of primary concern regarding public health. However, the pollution or ventilation of street canyons is governed by complex turbulent flow structures, which are affected by the geometrical features of street canyons and surrounding urban areas. Hence, the prediction of their pollution remains challenging [2–5].

Over the last two decades, numerous studies have focused on the effects of turbulent flow on street-canyon pollution in simplified [6–11] or real [12–17] urban areas. Irrespective of the methods used, either experimental (field or wind-tunnel tests) or numerical (computational fluid dynamics, CFD), these studies indicated the importance of the interactions between flow structures produced by street canyons and intersections because they result in more complex three-dimensional flows and have a different impact on the pollutant transport within urban areas than those observed for most studied 2D street canyons.

However, there is a lack of clarity about which flow features, turbulent or mean, govern the pollutant transport from or into street canyons with respect to the street-canyon geometry, that is, urban complexity. Kubilay et al. [18] demonstrated the importance of pollution fluxes for the investigation of street-canyon ventilation; the air-exchange velocity significantly underestimates the total pollutant exchange. There is a consensus among researches that vertical turbulent pollution fluxes govern the pollutant removal from a street canyon through its top opening. This consensus was reached for 2D [19–22] and 3D [6,23,24] urban models but for a simplified building geometry with flat roofs; the top opening was selected at the height of these roofs. This area has strong shear layers and vertical turbulent mass transport across these layers is dominant. However, in cases of more complex roof geometries, such as pitched roofs or nonuniform roof heights along street-canyon walls, the shear layer is spatially more complex [25–28] and there is no consensus at which height the top opening should be located. Recently, Nosek et al. [29] studied 3D street canyons with pitched roofs and nonuniform roof heights along each canyon wall and demonstrated that the dominance of the vertical turbulent transport of pollutant is strongly spatially dependent when the top opening was selected at the mean height of these canyons, irrespective of the wind direction. Roofs higher than the mean height resulted in the dominance

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of the vertical advection of the pollutant from or into the canyon through that opening [29]. Moreover, the selection of the mean height for the top opening in the case of roof height nonuniformity complicates the investigation of street-canyon ventilation because lateral gaps occur at that height compared with street canyons with uniform height. Consequently, one may ask at which height the street-canyon top opening should be located to assess the street-canyon ventilation in real urban environments and which flow features govern the pollutant transport from and into the canyon through the top opening at that height. As far as we know, these issues have not been addressed in prior studies.

The pollutant removal from 3D street canyons is more complicated than that in 2D cases due to the lateral openings, where pollutant exchange primary occurs in horizontal direction between the street canyon and intersections. Yet, recent findings of Carpentieri et al. [10] and Nosek et al. [30] obtained from wind-tunnel measurements of turbulent and mean pollution fluxes showed that the mean horizontal pollutant flux (hence the advection) dominates the horizontal transport of pollutants within the street network if the wind direction is oblique or parallel to the streets. Carpentieri et al. [10] concluded that further investigations are needed to clarify this finding, for example, that of the wind perpendicular to the streets in simplified geometries. However, more sophisticated techniques (e.g. large-eddy simulations, LES) are required due to the limitations of current wind-tunnel measuring techniques (suffering from similarity criteria).

Because of the resolving of large-scale turbulence with a length scale larger than the filter size (usually taken as the grid size), an LES model is more suitable for solving the above-mentioned issues than most of the used CFD models based on Reynolds-averaged Navier–Stokes equations (RANS) [3,31–33]. However, a validation of LES using experimental data needs to be performed prior to interpreting the results [2,3,5]. The objectives of the present study therefore are the following: i) to use an LES to investigate the street-canyon ventilation by means of turbulent and mean pollution fluxes at street-canyon openings; ii) to evaluate the LES by wind-tunnel measurements using the mean flows and concentrations and the turbulent and mean pollution fluxes of all investigated street-canyon openings; iii) to determine which flow features govern the street-canyon ventilation of each canyon opening; and iv) to investigate the impact of urban complexity on the street-canyon ventilation.

2. Methods

2.1. Wind-tunnel experiments

We used the results from our previous wind-tunnel experiments to evaluate the LES [29,30]. These experiments were conducted in the Environmental wind tunnel of the Institute of Thermomechanics of the Czech Academy of Sciences to investigate the mean and turbulent pollution fluxes at the openings of three different street canyons. The wind tunnel is an open low-speed wind tunnel with cross dimensions of 1.5 m × 1.5 m and the lengths of the development and test sections are 20.5 m and 2 m, respectively. The first reference street canyon (hereafter called A1-R) was part of an urban-like array model (Fig. 1a), with a scale of 1:400, formed by evenly spaced 8 × 4 courtyard-type buildings with constant length (L = 300 mm, i.e. 120 m at full scale) and width (W = 150 mm, i.e. 60 m at full scale) and pitched roofs with constant height H = 62.5 mm (i.e. 25 m at full scale, corresponding to the height of the roof ridges). The second (A2-R) and third (A2-L) street canyons were part of another urban-like array model, which had the same layout as the first model but arbitrarily distributed roof heights (0.8H, H, or 1.2H) along each building wall (Fig. 1b). However, each nonuniform street canyon has the same mean height as that of the urban model with constant roof height (H). Thus, both urban models have the same frontal ($\lambda_f = A_f/A_t = 0.27$, where A_f is the frontal area of the buildings viewed from the approach direction of the flow and A_t is the total ground area) and plan ($\lambda_p = A_b/A_t = 0.28$, where A_b is the area occupied by the buildings) solidities. The models were exposed to a simulated atmospheric boundary layer at the scale of 1:400 with the main aerodynamic parameters (roughness length, z_0 = 1.87 m; displacement height, d_0 = 3 m; and friction velocity, u_* = 0.43 m s^{-1}; all at full scale) and turbulent characteristics (streamwise and vertical intensities of turbulence of I_u = 35% and I_w = 25%, respectively) typical for European city centres [34]. Such a boundary layer was developed along the entire length of the wind-tunnel development section using the wall-mounted vortex (a set of three "Irwin spires", 1.4 m in height) and turbulent (thin squared plates; 50 mm in height) generators. Based on the building's mean height and freestream velocity U_{ref} = 6.2 m s^{-1} (which is used later as the reference velocity), the flow was fully independent of the Reynolds number (i.e. $Re_B = HU_{ref}/\nu \approx 24{,}400$, where ν is the kinematic viscosity of the air) according to [35], which was also confirmed by several independent tests.

The vertical mean and turbulent pollution fluxes at the top openings of all investigated canyons were measured during the first measurement campaign (Fig. 1e) [29]. The top opening was selected according to the lowest building wall of the nonuniform canyons, that is, at the height $z/H = 0.6$, which corresponds to the lowest eave of the nonuniform canyons and encloses each studied canyon from the top. During the second measuring campaign [30], we measured the lateral mean and turbulent pollution fluxes at each lateral opening of the investigated canyons (Fig. 1d), which encloses the canyons from the sides. The pollution was simulated with a 1 m long (=16H) ground-level line source (hereafter denoted as S1, see Fig. 1f), which ran continuously at the bottom of the centreline of the investigated street canyons and adjoining intersections. A passive gas (ethane) was homogenously emitted from that source at a constant flow rate of 18 ml s^{-1}. To measure both pollution fluxes, we simultaneously made point measurements of two velocity components (longitudinal and vertical for vertical fluxes or longitudinal and lateral for lateral fluxes) and the concentration employing a laser Doppler anemometry (LDA) and an HFR400 fast-response flame ionization detector (FFID), respectively (Fig. 2). This method was introduced by Carpentieri et al. [24] and Kukačka et al. [36] and is described in detail in our previous study [30]. For further details about the wind-tunnel experiments, we refer the reader to the latter study.

2.2. Large-eddy simulations

2.2.1. Model description

The LES computations were performed using an open-source[1] model called Extended Large-eddy Microscale Model (ELMM) to resolve the unsteadiness of the turbulent flow field. The ELMM was designed for simulations of turbulent flow and scalar transport under complex geometry and was recently used by Ref. [37]. The ELMM solves filtered incompressible Navier–Stokes equations:

$$\frac{\partial \vec{u}}{\partial t} + \nabla\cdot\vec{u}\,\vec{u} = -\nabla p + \nabla(\nu_{\text{eff}}\nabla\cdot\vec{u}), \tag{1}$$

where $\vec{u}$ is the resolved velocity vector, p is the pressure, ν_{eff} is the effective viscosity, and the continuity equation is:

$$\nabla\cdot\vec{u} = 0. \tag{2}$$

The effective viscosity ν_{eff} is the sum of the molecular viscosity ν and the eddy viscosity ν_{e} and must be modelled. In this study, the ELMM is based on the time-scale eddy viscosity subgrid model [38]. The wall shear stress is computed from the instantaneous velocity near the wall by a wall model with logarithmic wall function.

The filtered Navier–Stokes equations are discretized in time using the fractional step method with the third-order Runge–Kutta method.

[1] https://bitbucket.org/LadaF/elmm.