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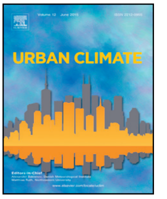

The pollutant removal capacity of urban street canyons as quantified by the pollutant exchange velocity

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ABSTRACT

In this work we investigate the representativeness of the pollutant exchange velocity as a quantitative metric for the actual pollutant removal capacity of a canyon under different pollution emission scenarios. We further explore its sensitivity to a change of the street canyon geometry aspect ratio as well as different exposure regions of interest within a 2-D canyon. We find that the effective pollutant removal capacity as quantified by the pollutant exchange velocity can vary substantially from its reference-nominal value as customarily derived for uniformly-distributed pollutant conditions in the canyon. We specifically find that for the case of the center and leeward wall locations of the source, the pollutant exchange velocity varied substantially exceeding a factor of 2 variations. Furthermore, we find that the highly nonhomogeneous pollutant distribution arising from the different source locations plays an important role in the pollutant removal rate accounting for both the turbulent and convective pollutant transport. As expected, the pollutant-exchange velocity was found to be dominated by the turbulent flux, reaching up to 2 to 3 times the convective pollutant flux at the rooftop level.

1. Introduction

Urban air quality and its impact on civilian health is becoming an increasingly important consideration in the planning and policy-making for healthy and climate-change resilient cities. Design of mitigation strategies

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for urban pollution exposure requires understanding of how air pollution from emission sources disperses within urban streets, e.g. at what rate it escapes from or accumulates within the streets. Air ventilation within urban street canyons is of rising importance mainly due to its link to the pollutant removal capacity of street canyons and subsequently to the long-term air pollution exposure of citizens. Different measures to quantify the pollutant removal capacity have been proposed such as breathability (Neophytou and Britter, 2005; Panagiotou et al., 2013; Neophytou et al., 2014) and mean age of air (Ramponi et al., 2015; Buccolieri et al., 2015). Such measures have been proposed mainly from the view point of characterizing on a bulk basis an urban street canyon itself (as part of a city) thus assuming some idealized prototype scenarios particularly concerning the pollution sources.

The air flow and pollutant dispersion within and above an urban street canyon is substantially determined by the presence of a shear layer generated at the rooftop level as well as the recirculation flows within the canyon. Shear layers with different thickness can be observed depending on the packing density of the canyons and additional roughness arising mainly at the roof surfaces. The nature of the shear layer at the rooftop level, its level of unsteadiness and thickness, determines the mean convective and turbulent fluxes through that level. The turbulent fluctuations within the shear layer are governed by coherent turbulent structures, which interact with each other across a wide range of spatial and temporal scales (Paterna, 2015). Such turbulent structures within shear layers can have a significant influence on pollutant and heat removal mechanisms in the built environment (Liu and Wong, 2014). Furthermore, the flow structures can also be different within street canyons depending on the geometry of the canyon e.g. on its aspect ratio, resulting in single or multiple recirculation regions within the street canyon. In addition, more complex and multi-scale effects can take place in urban atmospheres e.g. due to complex topographic terrain and land use variations (Fernando, 2010).

There has been substantial discussion in the literature on the urban air flow within street canyons under different conditions, e.g. for dense pollutant dispersion within isolated streets (Baratian-Ghorghi and Kaye, 2013), the flow and dispersion in unstable thermal stratification (Mei et al., 2016), and the impact of building configurations in isolated deep street canyons (Ng and Chau, 2014). Recently emphasis has been directed particularly to the capacity of urban street canyons to remove pollutants produced within (e.g. emissions from traffic or buildings). There are several definitions of exchange velocity in the literature that characterizes and quantifies the pollutant removal rate, e.g. air-exchange velocity which takes into account only the air-flow rate going out of a defined control volume (Bentham and Britter, 2003; Li et al., 2005; Liu et al., 2005; Cheng et al., 2008; Moonen et al., 2011; Panagiotou et al., 2013) or pollutant-exchange velocity which takes into account also the distribution of pollutant concentration (Buccolieri et al., 2015; Liu et al., 2005; Cheng et al., 2008). Such metrics are used to compare the influence of different building morphologies and wind-flow conditions on pollutant transport in urban areas. A summary of various studies on pollutant removal from street canyons and reported air-exchange velocities is given in Table 1 (Neophytou et al., 2014), where u_e denotes the air-exchange velocity and u_{ref} the reference velocity. The use of air-exchange velocity is practical as it can be obtained directly from air-flow simulations or measurements as a bulk air volume flux exchange rate per unit area of flow out of a considered control volume. The studies performed by Liu et al. (2005), Cheng et al. (2008) and Mirzaei and Haghighat (2011) have considered distinctly air-exchange velocity and pollutant-exchange velocity. Their analyses indicate different variations of these two exchange velocities to a certain variation in street-canyon aspect ratio. However, no direct evaluation is made comparing the reliability of the two exchange velocities in terms of the pollutant removal. Furthermore, even though the air-exchange velocity can be taken as a measure for ventilation efficiency of street canyons, no clear insight, either from theoretical or experimental evidence, is given that the rate of pollutant removal is directly related to air-exchange velocity.

Numerical simulations using Computational Fluid Dynamics (CFD) and experimental studies have been performed extensively in the literature to address wind flow and pollutant dispersion within the built environment. Reviews of CFD studies for pollutant dispersion is provided by Di Sabatino et al. (2013), Tominaga and Stathopoulos (2013), Blocken (2014) and Lateb et al. (2016). The most common models for air flow in urban environments are based on the Reynolds-averaged Navier-Stokes (RANS) equations which describe essentially the ensemble-average of the time-varying field. In the past, specific deficiencies of RANS k-ε modeling have been reported (Murakami, 1990, 1993; Tominaga et al., 2008a; Tominaga et al., 2008b), such as the overestimation of turbulence kinetic energy in the stagnation region at the windward facade, and the overprediction of the size of the wake and the location of reattachment due to the underestimation of turbulence kinetic energy in the wake of the building. As a result, pollutant dispersion studies using RANS models of

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