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Relating street canyon vertical mass-exchange to upstream flow regime and canyon geometry

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ABSTRACT

Understanding and management of air quality is important to the sustainability of the urban environment and pedestrian level air quality is strongly influenced by the vertical airflow and consequent pollutant mass transfer that takes place at the roof level of street canyons. Using data from a scaled wind tunnel street canyon flow, the present work shows how a simple, first order "dead-zone" model may be successfully applied to provide a link between the vertical velocities at roof level and the magnitude of the mass-exchange. In addition, it is shown how the model may be modified to provide a prediction that takes into account both the geometry of the canyon as well as the canyon flow characteristics and those of the upstream roughness. The mass-exchange is also shown to be linked to the largest scales in the boundary layer passing over the canyon. Finally, it has also been demonstrated that, for the six configurations investigated here (two canyon geometries immersed in three different types of upstream roughness), the probability distribution function of the exchange velocity agrees very well with a log-normal distribution, thus allowing derivation of a simplified model of the instantaneous exchange velocity using a random number generator.

1. Introduction

When considering the overall climate of a city, researchers have focussed on the urban heat island, in particular its effects on overall urban ventilation, building occupant and pedestrian comfort/health and building energy demand (Mirzaei, 2015). Although building-scale, micro-scale and city-scale models have been developed (Mirzaei, 2015), that link wind and thermal climate data to building energy models for example (Allegrini, Dorer, & Carmeliet, 2015), the wind flow prediction tends to be implemented via Computational Fluid Dynamics (CFD) models that consider only the time-averaged flow, despite the fact that the dynamic nature of the wind in the urban environment has yet to be elucidated, let alone quantified. Indeed, crucially, within a city there is an *intermittent* interaction between the atmospheric boundary layer flow and that within the individual street canyons, which governs the exchange processes of momentum, heat and pollutants, thus playing a critical role in the quality of the urban atmosphere and the sustainability of human life.

Although simple from a geometrical point of view, the idealized two-dimensional (2-D) street canyon model reproduces the main features of most common street configurations, notably the case for which the upstream wind is perpendicular to the street axis where the ventilation is largely driven by vertical exchanges between the canyon and the flow above. This configuration has been well-studied, with the time-averaged (steady) flow regimes being first identified by Hussain and Lee (1980) and then defined and illustrated by Oke (1988) as a function of the canyon streamwise width (W) to height (h) ratio. The three regimes – "skimming flow" when $W/h < 1.5$, "wake-interference flow" when $1.5 < W/h < 3$ and "isolated roughness flow" when $W/h > 3$ – have since been much-quoted in the literature even though, at the time he made these definitions, Oke (1988) noted that this classification ignored turbulence, that is any unsteady flow dynamics. The standard practical model that has been used for the past two decades to predict street canyon dispersion, the Operational Street Pollution Model (OSPM) (Berkowicz, 2000 and subject to numerous validation studies, Kakosimos, Hertel, Ketzel, & Berkowicz, 2011) considers the canyon flow to be a steady vortex with dispersion computed by a plume model. Although traffic produced turbu-

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lence (Di Sabatino, Kastner-Klein, Berkowicz, Britter, & Fedorovich, 2003; Kastner-Klein, Fedorovich, Ketzel, Berkowicz, & Britter, 2003) and meandering of the incident wind direction are considered, the unsteady canyon flow dynamics are not. Hence, in terms of urban air quality assessment, street canyon flows are conventionally considered to comprise one or more large-scale mean vortices, or flow recirculation regions, upon which relatively small-scale turbulence is superimposed. However, even on a time-averaged basis, there is no sharp demarcation of the regimes defined by Oke (1988), as illustrated from the Unsteady Reynolds-Averaged Navier-Stokes (URANS) CFD numerical model study of Sini et al. (1996), where the flow and pollutant concentrations were predicted for several canyon widths from $W/h = 0.33$ to 14.82, with the results showing continuous, though mostly gradual, changes in parameters such as canyon wall pressure coefficients, in-canyon wind speeds, dosing rate by an external source and the decay rate of pollutant from the street. The high degree of variability in basic aerodynamic parameters, such as roughness length, z_0/h, and zero plane displacement, d/h, for different planform geometries (2-D parallel streets, 3-D block regular arrays and real urban regions) having the same plan area packing density, λ_p, was highlighted by Grimmond and Oke (1999), where they also attempted to relate those parameters to the three flow regimes. Recently, the present authors conducted an approximately 1:250 scale wind tunnel study in which long canyons ($L/h = 30$) of two different widths $W/h = 1$ and 3 were placed normal to the oncoming flow in three different roughness arrays formed from; (1) cubes of height h with $\lambda_p = 25\%$, (2) 2-D square section bars of height h spaced $3\,h$ apart giving $\lambda_p = 25\%$ and (3) the same 2-D bars spaced $1\,h$ apart giving $\lambda_p = 50\%$ (Blackman, Perret, & Savory, 2015a). Instantaneous velocity vector fields were measured within and above the canyons for these six configurations, using Particle Image Velocimetry (PIV), from which mean and turbulence statistics were computed. For a given canyon width the flow was, indeed, dependent on the nature of the upstream roughness (2-D or 3-D) for the same plan area density. The streamwise velocities produced by the 3-D array were higher than for the equivalent 2-D array whilst the integral scales of turbulence were lower (although they increased with increasing 2-D roughness spacing, that is, the aspect ratio). In agreement with other published data, the relative contributions of the three orthogonal components to the total turbulent kinetic energy (TKE) showed that staggered and aligned arrays or 2-D and 3-D arrays of equal λ_p do not generate the same profiles of TKE (Rotach, 1995; Macdonald, Carter Schofield, & Slawson, 2002). Other workers have also shown that roughness type is important in determining the magnitude and distribution of the Reynolds stresses and the length scales in the roughness sub-layer (Volino, Schultz, & Flack, 2009; Lee, Sung, & Krogstad, 2011).

The ventilation rate of the canyon (important for local air quality), estimated via the computation of positive and negative (vertical) flow rate across the canyon opening, was also found to be influenced by the upstream flow regime, even with the narrow canyon of $W/h = 1$ (Blackman et al., 2015a). An upstream wake-interference flow regime (obstacle spacing of $3\,h$) led to stronger exchanges between the canyon and the flow above. For a given upstream roughness, changing from a skimming canyon flow ($W/h = 1$) to the wake interference flow regime ($W/h = 3$) increased the magnitude of the total positive and negative ventilation flow rates (i.e. the w' velocity fluctuations). This trend with canyon width was consistent with that found by Ho and Liu (2013), although the magnitudes of the non-dimensional ventilation flow rates, $Q/(U_e\,W\,L)$ (where U_e is the freestream velocity) were different in the two studies. All these findings emphasize that upstream roughness type and density play a significant role in determining the mean flow in a canyon of given aspect ratio, thus demonstrating the importance of carefully choosing the simulation method when carrying out wind tunnel studies of canyon flows, as noted previously by Savory et al. (2013). Indeed, when considering the classification of canyon regimes described here, based on the time-averaged flow, such a definition is made very unclear if the geometry of the canyon under consideration implies one kind of flow regime whilst the upstream roughness is defined as giving a different regime (Blackman et al., 2015a). When such considerations are taken into account alongside the fact that time-averaged canyon flow fields look very different from any instantaneous realization of the flow, one may reasonably question the practical value of this type of classification, especially when it comes to understanding the dynamics that actually govern canyon flow and dispersion. Hence, the present research has been motivated by a desire to seek a new classification of canyon regimes that incorporates the time-varying nature of the flow and its effects on canyon ventilation.

Urban canyon flows are dominated by vortical structures ("eddies") both within the oncoming boundary layer and generated locally by the flow around the canyon buildings and many researchers, for example Barlow and Leitl (2007), Coceal et al. (2007) and Perret and Savory (2013), have highlighted the strong unsteadiness of the flow developing at the building roof and its role in generating intermittent coherent turbulent structures which penetrate downwards, causing mixing of air in the street. The coupling between the large scale coherent structures in the boundary layer (associated with low and high momentum regions) and the smaller scales in the shear layer at the top of the canopy was observed by Takimoto et al. (2011) and Inagaki et al. (2012). In a PIV study of a $W/h = 1$ canyon the present authors used two-point spatial correlations, Proper Orthogonal Decomposition (POD) and spatial averaging to elucidate some of the aspects of the flow dynamics (Perret & Savory 2013). Strong ejection (Q2) and penetration (Q4) events were observed above the canyon up to a height of $z/h = 2$ and a non-linear coupling between the large-scales (identified through the first POD mode) and the smaller scales (other modes) was quantified. The experimental setup comprised a skimming flow regime canyon immersed in a roughness array formed from cubes of the same height as the canyon but with a plan area density corresponding to the wake interference. Thus, there was strong flow separation at the upstream edge of the upstream canyon obstacle that gave rise to a significant vertical "flapping" motion and a shear layer of thickness $O(h)$ in contrast to previous studies of similar canyons immersed in a skimming flow roughness where the shear layer was thinner, $O(0.2\,h)$, for example Salizzoni et al. (2011) and Kellnerová et al. (2012), because of separation occurring at the downstream edge of the upstream building in those cases. Hence, it is clear that any canyon classification model based on dynamics will have to consider both the local canyon geometry and the upstream roughness geometry.

The present work is a wind tunnel study at approximately 1:250 scale of two different canyons (aspect ratio $W/h = 1$ and 3) immersed in the same upstream roughness in which flow field measurements have been undertaken using PIV together with two reference hot-wire anemometers. The authors have already shown that the street canyon flow in this wind tunnel is well-scaled to published reference data for the same roughness (Blackman et al., 2015a) as well as to data from a field study of a similar type of idealized street canyon formed from shipping containers (Blackman, Perret, & Savory, 2015b; Perret, Blackman, & Savory, 2016). This prior work gives confidence that the wind tunnel experiment captures very well the dynamics of the full-scale case. The questions to be addressed in the present paper are:

(1) Can the vertical mass-exchange between the canyon and the boundary layer above be described by a relatively simple first-order "dead-zone" model and