Towards a classification of street canyon regimes based on flow dynamics
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Abstract
Street canyon flow regimes are classified using the time-averaged mean flow. The present paper discusses recent work on the dynamics of street canyon flows (important for pollutant transport) and the interaction with the shear layer and atmospheric boundary layer above, with a view to classifying the different regimes in terms of the unsteady characteristics of the flow for different types of canyon.

Introduction
In 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. Although simple from a geometrical point of view, the 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, the ventilation being mainly driven by the vertical exchanges between the canyon and the flow above. This configuration has been well-studied, with the steady flow regimes classified by Grimmond & Oke (1999) as a function of the canyon width (W) to height (h or H) ratio. The time-averaged (steady) canyon flow comprises a single vortex in the case of a square-section canyon or a combination of counter-rotating primary recirculations in the case of narrower canyons. Recent research has postulated, qualitatively, that the flow is dominated by vortical structures (“eddies”) both within the boundary layer and generated locally by the flow around the buildings. However, the connection between these flow structures is unknown and, hence, the mechanism of canyon ventilation unclear. Barlow & Leitl (2007), Coceal et al. (2007) and Perret & Savory (2012) 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. Top-down relationships between the large-scale structures from the boundary layer and events at the ground plane have been shown experimentally, Hutchins et al. (2011), in the case of a smooth ground. Using a relatively idealized building configuration, the present study aims at quantifying the unsteady behaviour of the flow and its implication in terms of canyon ventilation. Therefore, the focus is on the large-scale unsteadiness of the shear layer separating from an upstream canyon edge, its impact on the instantaneous flow field within the canyon and its link with the oncoming boundary layer. Consequences on numerical and physical modelling strategies are also discussed.

Wind tunnel and PIV setup
The results obtained in the present study are based on particle image velocimetry (PIV) measurements conducted in the atmospheric boundary layer wind tunnel of the LHEEA (Nantes, France). This facility has working section dimensions of 24 x 2 x 2 m and allows the generation of boundary layer
flows with free stream velocity ranging from 0 to 10 m.s\(^{-1}\). The test section has transparent side-walls and ceiling and the floor is equipped with a glass window, which permits optical access for both the laser and the PIV cameras. An example of the experimental setup is shown in Figure 1. Different types of roughness element arrangements (based on staggered cube arrays) of various packing densities can be installed in order to generate boundary layers of different characteristics, correctly scaled to the model under study, whether a street canyon (Savory & Perret, 2012, Perret & Savory 2012) or a cube array (Rivet et al., 2012). The reader is referred to these references for more details about the experimental setups and the generated boundary layers.

Unsteady organization of the street-canyon flow

*Insights from the PIV wind tunnel experiments*

In this section, brief examples of results obtained from the PIV measurements are provided to describe the main features of the dynamics of flows over urban-type terrain. Experiments conducted over a cube array corresponding to a wake interference flow regime showed that the instantaneous flow is dominated in the near canopy-top region by coherent structures generated by the obstacles, inducing a strong intermittent motion of penetration or ejection of fluid into or from the canopy, accompanied by well-identified vortices (Figure 1a).

Figure 2: a) Instantaneous PIV vector field above the staggered array of cubes showing a large scale sweeping motion well above the canopy, and shedding of vortical structures from an obstacle, generating local flow ejection and penetration (Rivet et al., 2012). b) and c) ensemble averaged ejection and penetration of fluid across the street canyon opening (Perret & Savory, 2012).
This canopy flow has been shown to be correlated with large-scale coherent structures existing in the boundary layer developing above (Rivet et al., 2012).

The results obtained for the street-canyon immersed in the same type of flow with a wake interference regime, as described above, evidenced several characteristics of unsteady flow organization. Indeed, the regime of the flow upstream of the canyon leads to a strong separation of the flow from the upstream obstacle, leading, in turn, to the formation of a shear layer. This shear layer develops over the top of the two obstacles and the canyon and is animated by a flapping motion that is found to induce intermittent penetrations or ejections of fluid from the canyon (Figure 2b, c), which are combined with vortical structures that irregularly penetrate into the canyon or are shed and convected in the outer flow, respectively. A non-linear coupling between the large-scale coherent structures from the boundary layer above, mainly corresponding to the low and high momentum regions, and the smaller-scales above the canyon has also been demonstrated (Perret & Savory, 2012).

**Conceptual model of the flow dynamics**

The characteristics briefly described above and their comparison with results from the literature obtained in different flow regimes (see Salizzoni et al., 2011 for instance) have several implications regarding the modelling strategies retained to investigate turbulent flows over and inside urban canopies. Indeed, the flow configuration studied here corresponds to the combination of a canyon immersed in a flow which belongs in the wake interference regime. The most obvious effect is that the flow separates at the upstream corner of the upstream building, instead of its downstream corner as it is the case when the upstream flow is in a skimming regime (Figure 3, left), leading to the formation of a shear layer of larger vertical extent above the canyon. In the present case, this shear layer is found to be animated by a strong flapping motion and sheds large-scale vortices alternatively inside the canyon and downstream in the flow above the roofs (Figure 3, right). A rough estimation of the thickness of the shear layer by estimating the vertical extent of the region of maximum shear stress existing at the top of the shear layer can range from 0.2h in the case of a skimming flow regime (Salizzoni et al., 2011) up to 1h in the case of a wake interference regime. The extreme case of skimming flow corresponds to the case where the canyon is modelled not as a pair of buildings protruding into the boundary layer flow but as a cavity cut into the ground. Even if very convenient to model, in particular from a numerical point of view, this kind of configuration can be expected to be far from realistic from a dynamical point of view. Although not studied in the present work, it can be inferred that such differences in the shear layer structure will have a strong impact on the transfer of momentum and scalars between the canyon and the overlying boundary layer.

A second important difference between the present study and some literature on canyon flows is the use of 3-D obstacles as upstream roughness elements to generate the atmospheric boundary layer as opposed to two-dimensional obstacles (Salizzoni et al., 2011. Recent studies based on DNS of boundary layer flows over rough walls have shown that the geometry of the roughness elements influences the characteristics of the flow in terms of Reynolds stress magnitude and turbulent length scales in the region corresponding to the roughness sub-layer (Volino et al., 2009; Lee et al., 2011). In particular, 2-D roughness elements were found to produce larger-scale ejections into the outer
boundary layer. It is, then, postulated here that the choice of the geometry of the upstream roughness elements will have an impact on the dynamics of the canyon flow. This influence will act through the perturbation of the separation mechanism of the flow from the building roof and via the influence of the boundary layer flow on the canyon through the non-linear interactions mentioned above.

Conclusions

Based on new wind tunnel experiments and comparison with the existing literature, the present study has provided an extension of the classification of the regimes of the steady flow proposed by Grimmond & Oke (1999) to the unsteady organization of the flow over a square-section street-canyon. The influence, on the dynamics of the canyon flow, of the flow upstream of the canyon and the geometry of the roughness elements used to generate that oncoming boundary layer is demonstrated. The influence of the geometrical parameters of the canyon such as height to width ratio, or length to height, on the flow dynamics will be the subject of future work.

References


