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Influence of urban morphology on air flow over building arrays

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ABSTRACT

In the present paper we have analysed experimentally (wind tunnel) and numerically (CFD) the impact of some morphological parameters on the flow within and above the urban canopy. In particular, this study is a first attempt in systematically studying the flow in and above urban canopies using simplified, yet more realistic than a simple array of cuboids, building arrays. Current mathematical models would provide the same results for the six case studies presented here (two models by three wind directions), however the measured spatially averaged profiles are quite different from each other.

Results presented here highlight that the differences in the spatially averaged vertical profiles are actually significant in all six experimental/numerical cases. Besides the building height variability, other morphological features proved to be a significant factor in shaping flow and dispersion at the local to neighbourhood scale in the urban canopy and directly above: building aspect ratio (or, conversely, the street canyon aspect ratio), the angle between the street canyons and the incoming wind and local geometrical features such as, for example, the presence of much taller buildings immediately upwind of the studied area.

1. Introduction

Air pollution in urban areas is an increasing concern, as the global urban population is growing in many countries. Recently, new concerns have arisen from the threat of accidental or deliberate release of hazardous gases in urban areas. There is a clear need of new mathematical tools capable of resolving the small spatial and temporal scales involved in the flow and dispersion phenomena in real complex cities. Computational fluid dynamics (CFD) models are currently capable of estimating the pollutant concentration field in small-to-medium sized spatial and temporal domains (Tominaga and Stathopoulos, 2013), but they are very time-consuming and, for air quality management and emergency response purposes, much faster mathematical models are needed. Such fast, approximate models should be able to parameterise the relevant variables in a complex urban environment while, at the same time, providing acceptable results in terms of accuracy and reliability.

High resolution urban models, especially at the local and intermediate (neighbourhood) scale, must take into account dispersion phenomena that occur in the urban canopy. The current approaches rely on empirical parametrisations derived from analytical studies and/or limited experimental data gathered mostly on very simplified geometries (e.g. single 2D street canyon or uniform arrays), or full scale measurements (usually very case specific). The influence of urban morphology on flow and dispersion in cities, and its parameterisation for urban flow and dispersion models has been studied, in the last couple of decades, either from a street canyon point of view (Theurer, 1999), or from a surface urban roughness point of view (Grimmond and Oke, 1999). The former relies on a description for the single street canyon based on canyon length (L), width (W) and height (H). The latter relies on surface roughness (z_0) and friction velocity (u_*) estimated from parameters such as the mean building height (H_b), the plan area index ($\lambda_p = A_b/A_t$, where A_b is the area occupied by the buildings, and A_t is the total area) and the frontal area index ($\lambda_f = A_f/A_t$, where A_f is the frontal area of the buildings in a given vertical section, which obviously depends on location and wind direction). Recent developments in three-dimensional urban digital databases allow for automatic calculation of such parameters using, for example, image-processing techniques (Ratti et al., 2002, 2006).

Experimental and numerical studies have been carried out in order to characterise flow and dispersion in typical urban roughness configurations (see, e.g., MacDonald et al., 1998a, 2000). They have led to the development of the few urban canopy models that are available today. These models usually assume spatially averaged velocity profiles, adopting an approach similar to that used for flow over vegetation canopies (Finnigan, 2000; Coceal and Belcher, 2004), and, in some cases, even a single spatially averaged

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canopy velocity (U_C, see Bentham and Britter (2003)). These properties depend strongly on the local geometry and existing models generally relate them to the mean building height (H_b) and the lambda parameters (λ_p, and λ_f, see above). Recent studies (Carpentieri et al. 2009, 2012a; Carpentieri and Robins, 2010; Harms et al., 2011; Klein et al., 2011), however, have highlighted the complexity of the flow and dispersion fields in actual urban geometries (as opposed to idealised building arrangements). It is clear from such studies that more parameters (such as building height variability and building aspect ratio) should be taken into account for a more accurate prediction of flow and dispersion in actual urban canopies.

Cheng and Castro (2002) performed wind tunnel experiments in building arrays with randomly distributed building heights, measuring velocity and turbulence in the roughness and inertial sub-layers. An interesting conclusion from their work is that cube arrays with variable height act as a substantially rougher surface than constant height arrays, even if the mean building height is the same. This is in contrast to all the current approaches described above where z_0 is only a function of mean building height and density. Xie and Castro (2006) and Xie et al. (2008) studied the same configurations by simulating the flow with both Reynolds-averaged Navier–Stokes (RANS) and large-eddy simulation (LES) CFD models. Their results showed that many features of the flow over the variable-height array are rather different from those in the flow over uniform roughness. They concluded that generalising modelling approaches derived from simpler (uniform) arrays is not a viable option for urban-like arrays, and more experimental and computational studies on this aspect are needed.

Another important aspect of the local urban geometry, the building aspect ratio (length: width: height), has received less attention. Most of the systematic studies on building arrays involve the use of cuboidal obstacles (Cheng and Castro, 2002; Cheng et al., 2007) or relatively deep and long street canyons (Kastner-Klein and Plate, 1999; Salizzoni et al., 2009). The few papers that consider a more realistic urban form usually tend to focus on diagonally symmetric buildings (width=length), so that fewer wind directions are needed to completely characterise flow and dispersion (Garbero et al., 2010). Building aspect ratios are expected to play a significant role in so-called 'topological dispersion' (Davidson et al., 1995; Jerram et al., 1995; Belcher, 2005), where the presence of the obstacle (building) enhances the lateral dispersion of the plume. This effect is greatly enhanced for some wind directions when the building has a form other than the classic cuboid, as evidenced in the few studies involving such types of buildings (see, e.g., MacDonald et al. (1998b), Yee and Biltoft (2004), and Milliez and Carissimo (2007)).

The present study has been carried out in the framework of the HRModUrb project (High Resolution Models for Flow and Pollutant Dispersion in Urban Areas), funded by the European Commission under the FP7-People Programme (Marie-Curie Actions). The overall objective was to study the effects of urban morphology on flow and dispersion phenomena at the local and neighbourhood scales, addressing the above issues. In the present paper, the effects of these parameters on the spatially averaged velocity profiles will be investigated through a series of systematic wind tunnel experiments, partially supported by some numerical CFD simulations

The specific objectives of the present study include:

1. measuring vertical wind profiles in urban models with different morphological characteristics;
2. assessing the influence of building height variability;
3. investigating the influence of building aspect ratio with respect to wind direction;
4. evaluating the representativeness of spatially averaged wind profiles and canopy averaged velocities.

2. Wind tunnel experiments

2.1. The models

The aim of the present study was to investigate the effect of morphology on flow and dispersion in realistic urban environments. In order to do this, the development of urban models more complex than the usual array of cubic buildings was necessary. However, the models had to be simple enough that a systematic study and a relatively easy parameterisation could be possible.

The starting point for the design of the models was the 1:200 scale model of the DAPPLE field site in central London (Arnold et al. 2004, Carpentieri et al. 2009). A substantial amount of data has been gathered in wind tunnel experiments, field tests and numerical simulations for the DAPPLE site, and these data can be used in future as comparison for the simpler models.

The models designed for this study are again at a nominal scale of 1:200 and have two main intersecting streets (approximately matching those of the DAPPLE site: Marylebone Road, along the x axis, and Gloucester Place, along the y axis) and several smaller streets. The dimensions (width) of the main streets are, respectively: 220 mm and 110 mm (44 and 22 m at full scale). The building blocks occupy an area of 230×350 mm^2 (arranged with the longer dimension along the y axis). In order to match the DAPPLE site $\lambda_p = 0.54$, an array of 6×8 buildings was built, with the width of the secondary streets equal to 99 mm (see Fig. 1).

Two models were employed in order to investigate the influence of the building height variability on the flow and dispersion phenomena, one with constant building height and the other variable building height. The simplest model (named 'SimpleC') had a constant building height ($H_b = 102$ mm, which is the mean building height of the central part of the DAPPLE model). The other model ('SimpleV') was designed with five different building heights. The height of the DAPPLE model buildings were divided into five classes of height ranges (55–75 mm, 75–95 mm, 95–115 mm, 115–155 mm, and 155–170 mm) and the distribution of the building heights in SimpleV matched that of the DAPPLE model. A building height of 102 mm was chosen for the 95–115 mm class for practical convenience. The other building heights were adjusted in order to give the required overall mean height (i.e. 102 mm), λ_f (0.24 for wind direction parallel to the x axis, and 0.16 for wind direction parallel to the y axis) and height variability ($\sigma_H = 32$ mm) as the DAPPLE model. It comprises the following buildings: $8 \times H_1$ (65 mm), $20 \times H_2$ (85 mm), $8 \times H_3$ (102 mm), $4 \times H_4$ (135 mm), and $8 \times H_5$ (162 mm). The distribution of the different buildings in the model was defined to provide a symmetric distribution along both axes, with the four central buildings chosen among the H_3 class, in order to have similarity in the central part of the model between SimpleC and SimpleV.

The coordinate system used throughout the paper is aligned with the models. The x axis is always parallel to the largest street, with the y axis perpendicular to it with an origin in the centre of the model (see also Figs. 2 and 3).

2.2. Experimental strategy

The experiments were carried out at the boundary layer wind tunnel of the Environmental Flow Research Centre (EnFlo), University of Surrey, UK. It is an open circuit 'suck-down' wind tunnel with a 20 m long, 3.5 m wide and 1.5 m high working section. The