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Mean and turbulent mass flux measurements in an idealised street network☆

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ABSTRACT

Pollutant mass fluxes are rarely measured in the laboratory, especially their turbulent component. They play a major role in the dispersion of gases in urban areas and modern mathematical models often attempt some sort of parametrisation. An experimental technique to measure mean and turbulent fluxes in an idealised urban array was developed and applied to improve our understanding of how the fluxes are distributed in a dense street canyon network. As expected, horizontal advective scalar fluxes were found to be dominant compared with the turbulent components. This is an important result because it reduces the complexity in developing parametrisations for street network models. On the other hand, vertical mean and turbulent fluxes appear to be approximately of the same order of magnitude. Building height variability does not appear to affect the exchange process significantly, while the presence of isolated taller buildings upwind of the area of interest does. One of the most interesting results, again, is the fact that even very simple and regular geometries lead to complex advective patterns at intersections: parametrisations derived from measurements in simpler geometries are unlikely to capture the full complexity of a real urban area.

1. Introduction

Modelling air pollution in urban areas has become more and more important in recent years when potential health problems might arise from traffic emissions as well as accidental or deliberate releases of hazardous gases. Mathematical models for real urban areas should take into account a wide range of spatial and temporal scales. Computational fluid dynamics (CFD) models can adequately simulate small and medium sized urban regions (Tominaga and Stathopoulos, 2013), but they have too time-intensive to be used for air quality management or rapid response in case of an emergency. For this purpose, fast approximate models are better suited to provide a rapid answer and they must be able to both parametrise the physical phenomena in a complex geometry and giving accurate and reliable results.

One of the many complications that exist in real urban areas is represented by street canyons that are often pollutant hot-spots. Contrary to the classical definition (infinitely long street with buildings on both sides), in actual cities their length is limited and they are not isolated, being connected to other streets at intersections. Dispersion in street canyon intersections is still rarely studied (see, e.g., Hoydysh and Dabberdt, 1994; Scaperdas, 2000; Carpentieri et al., 2009; Carpentieri and Robins, 2010) compared to isolated canyons. Pollutant can be exchanged between several streets and with the flow above the canopy at urban intersections and a better knowledge of these transport processes is very important for developing reliable mathematical parametrisations. Real intersections, however, are often characterised by highly three-dimensional flows and are not easy to study in a systematic manner.

To make matters more complicated, both advective and turbulent mass exchanges play a significant role in transferring gases in and out of the street canyons (Caton et al., 2003; Salizzoni et al., 2011). Despite this, very few experimental studies of urban-like models (Carpentieri et al., 2012) focussed on turbulent fluxes, mainly because the simultaneous measurement of velocity and concentration in laboratory is very hard to achieve.

Fackrell and Robins (1982), Zhu et al. (1988) and Lemoine et al. (1997) applied conventional measurement techniques, such as the combined use of hot wire anemometry (HWA) and tracer

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concentration fluctuation measurements, to quantify turbulent mass fluxes in wind tunnel experiments. The first use of conventional techniques to measure turbulent mass fluxes in an urban model, and in particular within street canyons and intersections, was that of Carpentieri et al. (2012), who combined laser Doppler anemometry (LDA) and fast flame ionisation detector (FFID) measurements to derive pollutant exchanges in a complex London neighbourhood.

Other authors derived alternative measurement techniques to be used in urban models. Dezső-Weidinger et al., 2003 used particle tracking velocimetry (PTV) to assess whether turbulent mass fluxes are proportional to concentration gradients in a regular-shaped two-dimensional street canyon. They found that this common assumption does not hold in the canopy region. Integral mass flux calculations were not attempted in their study. A similar study in a water flume was carried out by Caton et al. (2003) with the aim of validating their pollutant mass exchange parametrisation, but they neglected turbulent fluxes.

Barlow and Belcher (2002) used naphthalene sublimation to estimate spatially averaged total mass fluxes (see also Barlow et al., 2004; Pascheke et al., 2008), but this technique cannot separate the advective from the turbulent components. Similarly, Narita (2007) used water evaporation instead of naphthalene. Another similar approach would involve the use of heat as an analog for mass and measuring heat fluxes.

Urban dispersion models can range from simple street canyon approaches (e.g. ADMS-Urban, McHugh et al., 1997), to street network models (e.g. SIRANE, Soulhac et al., 2011), to full building-resolved CFD models. They all rely on some sort of parametrisation of the pollutant mass transfer within and above the street canopy, and these are particularly important for street network models (Ben Salem et al., 2015; Belcher et al., 2015). There is a need, then, to produce experimental data sets that can be used to validate these parametrisations (Gamel et al., 2015).

This and the results from previous wind tunnel experiments (Carpentieri et al., 2009; Carpentieri and Robins, 2010) motivated the development a robust technique to measure both advective and turbulent mass fluxes and be able to assess their individual contributions. This technique was developed and preliminarily tested in the DAPPLE model by Carpentieri et al. (2012). The application of simultaneous LDA and FFID measurements proved extremely useful in assessing pollutant fluxes around street intersections, but the geometrical complexity of the model posed many obstacles, first of all the fact that, because of the difficulties in identifying a “roof level” when all buildings heights were different, a vertical pollutant exchanges between the urban canopy and flow above could not be directly measured but only indirectly estimated. A similar technique, with a coupled HWA-FFID method, was subsequently applied to the flow around a 2D obstacle in the detailed study by Gamel (2015) and Gamel et al. (2015), but no measurements were made in more complex settings such as street canyons or intersections.

The present study uses the technique developed by Carpentieri et al. (2012), but the wind tunnel experiments are applied to more regular models of idealised urban street networks. The same technique was applied to more complex urban arrays by Nosek et al. (2016, 2017). Their results, while interesting, are not directly comparable with the present study due to the large differences in the studied geometry, especially as far as the roofs are concerned.

In the present study, the measurements are taken around a central intersection where all the buildings have the same height, thus allowing a direct measurement of vertical exchanges. The study is part of the HRModUrb project (Carpentieri, 2013) and follows up flow measurements and numerical simulations carried out to assess the influence of urban morphology (in particular building height variability) on flow and dispersion in urban street networks (Carpentieri and Robins, 2015).

The main objectives of this work are: (i) to study the feasibility of using this technique to measure pollutant fluxes in complex urban models; (ii) to understand the processes driving vertical and horizontal pollutant exchanges in building arrays; and (iii) to derive integral mass exchange balances.

2. Experimental setup

The two idealised urban models used in this study were described in detail by Carpentieri and Robins (2015). They were developed using morphological parameters from the central region of the DAPPLE site in London, in particular as far as building area density ($\lambda_p = 0.54$) and mean building height ($H_b = 102$ mm) are concerned. “SimpleC” is the first model, with all buildings of the same height. “SimpleV”, the second model, has the same building density and mean height, but it includes blocks with different heights. The standard deviation of the building heights is the same as in the DAPPLE site ($\sigma_H = 32$ mm) as well as the frontal area densities for the two wind directions ($\lambda_f = 0.25$ along the x axis, $\lambda_f = 0.16$ along the y axis). Further details can be found in Carpentieri and Robins (2015) and supplemental material.

The EnFlo boundary layer wind tunnel at the University of Surrey, where the experiments were carried out, is an open circuit wind tunnel (test section: 20 m × 3.5 m × 1.5 m). The reference flow velocity is measured by an ultrasonic anemometer outside the generated boundary layer. Tracer concentrations were measured by a fast response Flame Ionisation Detector (FFID), while velocities were investigated by means of a two-component Laser Doppler Anemometer (LDA). This setup allows the simultaneous measurements of concentration and velocity, as described by Carpentieri et al. (2012), thus enabling the estimation of both the mean and turbulent scalar fluxes. The averaging time was around 70 s in most measurements, so that typical values for the standard errors were around 2% for the mean velocity, the vertical velocity variance and both the concentration mean and variance, and around 3% for the horizontal velocity variance.

For this series of experiments, two model orientations were tested: 90° (wind aligned with the y axis) and 45°. The experiments were performed using a reference wind speed $U_{ref} = 2.0$ m s^{-1}. The approach flow obtained is fully described by Carpentieri and Robins (2015). Roughness length and friction velocity were estimated from the logarithmic profile fit: $z_0 = 0.015 H_b$ and $u_* = 0.06 U_{ref}$. The measurements were located around the central intersection covering an horizontal layer at roof level (Fig. 1a), and the inlet and outlet vertical sections of the 4 streets around the intersection (Fig. 1b and c), covering the volume of interest with a reasonably high spatial resolution. The present study is mainly concerned with scalar fluxes, so for each measurement section (surface), the relevant velocity component has been measured: that includes the W component in horizontal sections (i.e. vertical component through the roof level areas), the U component in vertical sections perpendicular to x (i.e. horizontal fluxes along X-street) and the V component in vertical sections perpendicular to y (i.e. horizontal fluxes along Y-street).

The source for the tracer measurements was located as shown in Fig. 2 so that at the intersection we could claim to be in the *intermediate-field* regime (a few street canyons downstream in all cases). Measuring mass fluxes in the *far-field* is, in fact, not very useful, as concentrations would be uniform across the different regions. While the ultimate goal is to be able to measure mass fluxes and produce reliable exchange balances for the *near-field* regime, we have decided to test our methodology in an easier situation. In the intermediate-field dimensions of the dispersion