Atmospheric Environment 43 (2009) 5027–5037

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

A field study of factors influencing the concentrations of a traffic-related pollutant in the vicinity of a complex urban junction

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ARTICLE INFO

Article history:
Received 18 February 2009
Received in revised form
28 June 2009
Accepted 29 June 2009

Keywords:
Dispersion
Intersection
Street canyon
Traffic pollution
Turbulence
DAPPLE field campaign

ABSTRACT

The paper describes a field study focused on the dispersion of a traffic-related pollutant within an area close to a busy intersection between two street canyons in Central London. Simultaneous measurements of airflow, traffic flow and carbon monoxide concentrations ([CO]) are used to explore the causes of spatial variability in [CO] over a full range of background wind directions. Depending on the roof-top wind direction, evidence of both flow channelling and recirculation regimes were identified from data collected within the main canyon and the intersection. However, at the intersection, the merging of channelled flows from the canyons increased the flow complexity and turbulence intensity. These features, coupled with the close proximity of nearby queuing traffic in several directions, led to the highest overall time-average measured [CO] occurring at the intersection. Within the main street canyon, the data supported the presence of a helical flow regime for oblique roof-top flows, leading to increased [CO] on the canyon leeward side. Predominant wind directions led to some locations having significantly higher diurnal average [CO] due to being mostly on the canyon leeward side during the study period. For all locations, small changes in the background wind direction could cause large changes in the in-street mean wind angle and local turbulence intensity, implying that dispersion mechanisms would be highly sensitive to small changes in above roof flows. During peak traffic flow periods, concentrations within parallel side streets were approximately four times lower than within the main canyon and intersection which has implications for controlling personal exposure. Overall, the results illustrate that pollutant concentrations can be highly spatially variable over even short distances within complex urban geometries, and that synoptic wind patterns, traffic queue location and building topologies all play a role in determining where pollutant hot spots occur.

1. Introduction

Urban areas are susceptible to elevated concentrations of pollutants due to the high density of traffic and the dense arrangement of buildings that modifies the airflow and can inhibit the ventilation of pollutants emitted at street level. The accurate prediction of concentrations, necessary for air quality management, requires knowledge of the modified wind flow between buildings which affects dispersion and entrainment mechanisms, as well as the magnitude and location of traffic emissions. Many previous studies of dispersion within urban areas have concentrated on the idealised case of the 2D street canyon (Sini et al., 1996; Pavageau and Schatzmann, 1999; Louka et al., 2000). The skimming flow regime that may occur during near perpendicular winds for canyons with height to width ratios between 0.65 and 1 (Oke, 1987; Leonardi et al., 2003) has received much attention, since pollutants released by vehicles at street level are then transported by a single across-canyon vortex leading to elevated concentrations on the canyon leeward side. The presence of such a cross canyon vortex may also affect the extent of vertical mixing as well as turbulence levels and thus the mean and turbulent flux of pollutants out of the canyon (Baik and Kim, 2002). The dependence of vortex structure on canyon aspect ratio was studied using a Reynolds Averaged Navier Stokes (RANS) model by Baik and Kim (1999).

As pointed out in Ahmad et al. (2005), less attention has been paid to airflow patterns established under oblique background

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doi:10.1016/j.atmosenv.2009.06.047

winds than under perpendicular ones. Given the fluctuation of background flows in real urban scenarios, it is important to understand the dependence of in-street flows on background wind speed and direction. The formation of helical vortices under oblique background flows, has been observed in canyon studies in the field by DePaul and Sheih (1986), Nakamura and Oke (1988), Longley et al. (2004), Boddy et al. (2005), Eliasson et al. (2006) and in wind tunnel studies such as Hoydysh and Dabberdt (1988). A helical flow regime was also indicated for a range of background wind directions in a RANS numerical study of a realistic urban geometry by Dixon et al. (2006). Smalley et al. (2008) showed that in a street canyon in York, UK, both the in-street mean flow angle and the local turbulence intensity were strongly affected by the orientation of the above roof flow with respect to the mean canyon direction. In a numerical study into the effects of background wind direction on flow and dispersion in short street canyons (Kim and Baik, 2004), three in-canyon flow patterns were identified with considerably different dispersion characteristics depending on the incident wind angle. The study showed that as the angle of incidence became oblique to the street axis, more pollutants escaped from the street canyon. Scaperdas and Colvile (1999) estimated through combined analysis using field data and a RANS code, that a change in wind direction could result in an increase or decrease of monitored CO concentration of up to 80%, for a given level of traffic emissions and meteorological conditions at the Marylebone Road monitoring station in central London.

The street canyon therefore seems to be a useful canonical form that helps to explain the influence of background airflows on in-street turbulent velocity profiles and dispersion for a number of previous field, wind tunnel and numerical studies. Most cities however, consist of complex road networks incorporating not just street canyons, but also intersections and side streets. The field measurements of Smalley et al. (2008) and numerical modelling of Dixon et al. (2006) illustrated that the presence of side streets can lead to converged flow within the main canyon for certain background wind angles, with associated large increases in local turbulence intensities and mean flow updraughts near the convergence point. The exchange of pollutants at intersections has been shown to play an important role in the dispersion of pollutants through networks of urban streets (Scaperdas and Colvile, 1999; Robins et al., 2002). Intersections provide a mechanism for airflow branching and therefore pollutant exchange at street level and could potentially show different levels of local turbulence intensity than within uninterrupted street canyons. Intersections are clearly an important part of the urban form and will vary in their geometric structure depending on the nature of the adjoining canyons. Robins et al. (2002) showed that small asymmetries in intersection geometry or background wind direction can lead to very different dispersion patterns.

Detailed numerical studies based on RANS (Chang and Meroney, 2003; Di Sabatino et al., 2007), higher order turbulence closure models such as Large Eddy Simulation (Xie and Castro, 2006) and even direct numerical simulation (Coceal et al., 2006, 2007) have now begun to move on from classical canyon structures to investigate flows through arrays of obstacles. Studies often tend to focus on spatially averaged quantities such as mean velocities, turbulent stresses and drag, although Coceal et al. (2007) demonstrated that the spatial variances of turbulence statistics are very significant within the canopy layer of regular arrays of cubic obstacles. There are still however, few studies which focus on flow patterns and pollution exchange at the intersections themselves. This type of exchange has been addressed more recently through operational network models (Hamlyn et al., 2007; Soulhac et al., 2009) using parameterised rates of exchange between regions of flow at the neighbourhood scale. The evaluation of such operational models using data from detailed modelling, wind tunnel and field experiments in real street environments is vital.

A range of field studies are therefore necessary in order to assess whether features such as cross canyon vortices and helical flows are relevant to a wide variety of real city environments, and as to whether additional features such as mean updraughts may result from the presence of side streets and intersections. The influence of such features on the dispersion of traffic-related pollutants is of importance in determining the key factors that may affect roadside concentrations and therefore exposure within urban environments. In addition, despite the relatively good coverage of monitoring stations within urban areas, questions remain as to whether they accurately reflect the potentially broad range of pollution levels experienced within urban streets where concentrations can vary greatly within a very small distance depending on local meteorology, traffic movements and emissions generated. Geometric intersections are also often traffic intersections, with associated congestion on the branches of the traffic junction. Significant sources of traffic-related pollutants are therefore likely to be present at intersections leading to exposure of people passing through the junction. Personal exposure to pollutants is heavily dependent on in-street location, and it is therefore important to determine the causes of variability in personal exposure to air pollution, including in the vicinity of intersections. To explore the impact of such complexities, this study focuses on a busy intersection between two street canyons (Marylebone Road and Gloucester Place) in central London (NW1) and forms part of the DAPPLE (Dispersion of Air Pollution and Penetration into the Local Environment) field campaign (Arnold et al., 2004). Simultaneous measurements of airflow, traffic flow and CO concentrations ([CO]) are used to explore the causes of spatial variability in [CO] over a full range of background wind directions. The experimental methodology underpinning the field study is explained in Section 2. Section 3 presents discussion of the mean airflow characteristics, turbulence profiles and pollutant concentrations under varying background wind speeds and directions. Overall conclusions and the significance of the results are explained in Section 4.

2. Methodology

2.1. The DAPPLE field site

Marylebone Road is a busy 6-laned major arterial road and forms the northern boundary of the London congestion charging zone. Gloucester Place is a one-way, 3-laned street. The streets intersect perpendicularly and were shown in Dobre et al. (2005) to demonstrate canyon type flows at distances of greater than 25 m away from the intersection. An overview of DAPPLE and a comprehensive description of the experimental site in 2003 and set-up are presented in Arnold et al. (2004) and at www.dapple.org.uk. Fig. 1a presents a schematic view of a subsection of the site showing the position of instruments used in the present analysis and the main location and direction of traffic queues around the intersection. The buildings adjacent to the intersection with heights varying as shown in brackets include; Westminster Council House (WCH) (15–19 m); Marathon House (10–14 m), which also has an office tower-block section over 50m high; Bickenhall Mansions (20–24 m) and Dorset House (30–34 m). The intersection is therefore asymmetric in terms of building heights. In addition, the geometry of Marathon House on the NNE corner is unusual, in that the building contains an arc shaped edge as shown in Fig. 1a. Throughout, all angles show direction *from* which the wind is coming (in degrees, increasing clockwise) relative to Marylebone Road where 0° indicates winds from the west-south-west.