Original article

Air quality affected by trees in real street canyons: The case of Marylebone neighbourhood in central London

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ABSTRACT

This paper discusses the combined influence of building morphology and trees on air pollutant concentrations in the Marylebone neighbourhood (central London). Computational Fluid Dynamics (CFD) simulations are performed with OpenFOAM using the k-ε model. Aerodynamic and deposition effects of *Platanus acerifolia* trees are considered. While aerodynamic effects are treated as typically done in the literature, i.e. as a porous media, for the deposition an enhanced model with an additional sink term was implemented. CFD results are compared with UK AURN (Automatic Urban and Rural Network) station concentrations. Several meteorological conditions are analysed based on London City Airport weather station data, with attention to prevailing winds.

CFD simulations show that trees trap air pollution by up to about 7% at the Marylebone monitoring station in the spring, autumn and summer seasons, suggesting that the aerodynamic effects are similar over the different leaf seasons. Aerodynamic effects are more important at lower wind speeds causing little turbulent dispersion. Deposition effects are found to be 4 times less important with reductions of up to about 2%, with more deposition in summer due to a greater leaf area density. Furthermore, for winds parallel to Marylebone Road, the aerodynamic effects decrease concentrations suggesting that in such cases trees could be considered as a mitigation measures. This is different from perpendicular winds for which trees exacerbate trapping, as found in previous studies. The analysis of concentration levels obtained from CFD simulations across the whole street confirms a beneficial aerodynamic dispersive effect of trees of 0.7% in summer time for all wind directions averaged at a wind speed of 5 m/s (yearly average wind speed observed in the area). Results highlight the need to account for both aerodynamic and dispersion effects of trees in CFD modelling to achieve a comprehensive evaluation and help city planners with a sustainable design of trees in urban environments.

1. Introduction

Many municipalities have shown a renewed interest in "urban forestry" by incorporating green space and vegetation into the urban environment. Urban greening usually refers to urban design elements such as trees and other plants in parks, sidewalks or elsewhere, employed for recreation or aesthetic improvement of a city. In recent years, researchers have also been looking into potential benefits of green space and vegetation, including lower energy use, reduced air pollution (Gallagher et al., 2015; Gromke et al., 2016; Li et al., 2016), protection from harmful exposure to ultraviolet rays, heat island mitigation, decreased storm water runoff, potential reduced pavement maintenance (Roy et al., 2012; Maggiotto et al., 2014; Di Sabatino et al., 2015; Hsieh et al., 2016), improved wellbeing of the urban population (White et al., 2013; Van den Berg et al., 2015) and reduced traffic noise levels (Kalansuriya et al., 2009). Although particle deposition on plant surfaces removes pollutants from the atmosphere, thus reducing their concentration, it also should be noted that trees themselves act as obstacles to airflow decreasing air exchange and leading to larger pollutant concentrations.

Several experimental and modelling studies on the effects of trees on urban air quality have been performed in the recent literature (most of them have been collected in reviews by Janhall,

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2015 and Gallagher et al., 2015). One of the pioneering experiments was performed in the wind tunnel of the University of Karlsruhe (CODASC, 2008) where pollutant concentrations were measured at the leeward and windward of isolated symmetric street canyons of several aspect ratios and approaching wind directions. Trees were found to increase wall-averaged concentrations up to about 100%. Results also showed that street-level concentrations crucially depend on the wind direction and street canyon aspect ratio rather than on tree crown porosity typically found in real scenarios and stand density. Several Computational Fluid Dynamics (CFD) models were then applied to simulate the CODASC case and parameterizations of aerodynamic (e.g. Buccolieri et al., 2011; Wania et al., 2012; Amorim et al., 2013; Gromke and Blocken, 2015a,b) and deposition effects of trees (e.g. Jeanjean et al., 2015, 2016; Santiago et al., 2016; Selmi et al., 2016) were developed and employed in simulations of flow and pollutant dispersion within complex geometries and real scenarios. Among the most recent studies, Gromke and Blocken (2015b) found low to moderate increases (up to about 13%) of pollutant concentration at pedestrian level in generic urban neighbourhood for various avenue-tree layouts (only considering aerodynamic effects), with pronounced locally restricted decreases or increases (−87 to +1378%). Santiago et al. (2016) reported decreased concentrations close to the ground up to 60% in several idealized arrays of different packing density depending on the deposition velocity, showing that the deposition effects are also crucial in determining the final concentration levels. Real scenarios were simulated by several authors such as Amorim et al. (2013) who investigated the aerodynamics effects of trees in selected areas of Lisbon and Aveiro (Portugal) for distinct relative wind directions, showing an average 12% increase of concentrations and an average 16% decrease for oblique and parallel wind directions, respectively. Jeanjean et al. (2015, 2016) also found that trees are beneficial from a purely dynamic point of view, as they decreased concentration of traffic emissions by 7% on average at pedestrian height in a neighbourhood in Leicester (UK). Recently, Gromke et al. (2016) showed a reduction up to 60% at pedestrian level in the presence of continuous hedgerows. These results show that the effects of trees and urban vegetation in general are strictly dependent on their interaction with geometry and meteorological conditions. Studies tend to agree that aerodynamic effects of trees are more signification than deposition (Vos et al., 2013; Jeanjean et al., 2016). Even though challenges and strategies for urban green-space planning in compact cities have been proposed (Haaland and van den Bosch, 2015), this topic needs to be further investigated before any action is taken in urban planning (Janhall, 2015).

Within this context, the objectives of the present study are twofold. The first objective is to validate a CFD dispersion model of NO_x and $PM_{2.5}$ (using the CFD code OpenFOAM) to account for the aerodynamic effects of trees in combination with the deposition effects for $PM_{2.5}$. This allows a comprehensive evaluation of the effects of trees on pollutant dispersion. The second objective is to apply the developed methodology to investigate the effects of trees on dispersion in a real scenario, i.e. in Marylebone neighbourhood in central London. CFD results are compared with concentration data from monitoring stations available from the UK AURN (Automatic Urban and Rural Network). Several meteorological conditions have been chosen based on data retrieved from the London City Airport weather station, paying particular attention to the prevalent wind speeds and directions.

The paper is structured as follows. Section 2 describes the study site and the cases investigated. Section 3 describes the general CFD modelling and the modelling of trees, with details on the development of the deposition module. Section 4 presents the results and discusses the effects of trees on affecting road emission concentrations. Conclusions are given in Section 5.

2. The study site

2.1. Description of geometry and trees

Marylebone is an affluent inner-city area of central London (UK), located within the City of Westminster. It is characterised by major streets on a grid pattern such as Marylebone Road, one of the busiest roads of central London, with smaller mews between the major streets. The area is characterized by a geometry typical of the architecture of many European cities with several street canyons (Di Sabatino et al., 2010). Marylebone Rd is characterised by a street canyon configuration with an aspect ratio (height over width) near unity (Nikolova et al., 2016). It usually experiences high pollution episodes due to the passage of more than 80,000 vehicles per day on Marylebone Rd and regular traffic congestion (Crosby et al., 2014). This makes it one of the most polluted sites in the UK, with an average NO_2 concentration of 94 $\mu g\,m^{-3}$ in 2014, according to the AURN measurements. Well above the European recommended threshold of 200 $\mu g\,m^{-3}$, pollutant concentration thresholds are regularly exceeded up to 35 times a year (Charron et al., 2007).

Roads, buildings and trees data were integrated to reconstruct a 3-dimensional (3D) area around the study area. Roads and buildings data were taken by Ordnance Survey which is the UK governmental mapping agency (OS, 2016). The National Tree Map^{TM} (NTM) Crown Polygon produced by Bluesky International Ltd was used to represent individual trees or closely grouped tree crowns (Bluesky, 2016). Trees and bushes over 3 m in height were included in the database. An overview of the study area can be seen in Fig. 1. The NTM^{TM} product provides a canopy top height but does not however provide a canopy base height. Therefore, a canopy base height of 1/3 of the canopy depth was assumed, as is commonly done in current literature (e.g. Gromke et al., 2008; Gromke and Blocken 2015b).

2.2. Description of the cases investigated

Several cases have been simulated with the CFD code OpenFOAM (Table 1). Wind data for the year 2014 were retrieved from the London City Airport weather station (EGLC, available at https://www.wunderground.com), every 30 min with a wind direction accuracy of 10°. The station is located around 15 km west of the monitoring site. In 2014, the recorded average wind speed was 4.3 m/s and the prevalent wind direction was South-West (Fig. 2). Specifically, 4 wind speeds and 15 wind directions were selected, i.e. every 30° in the range 270°–180°, and every 15° in the range 180°–270°, the latter being the prevailing wind direction range found in the study area.

Leaf-free trees (winter, referred to as CB), trees with half-grown leaves (spring/autumn, referred to as CT1) and trees with fully grown leaves (summer, referred to as CT2) were investigated for each wind speed and direction. Scenarios CT1 and CT2 have been modelled with different porosities (see Subsection 3.3 and Table 3 for further details). Overall, 4 wind speeds, 15 wind directions, 3 different tree profiles and 2 pollutant species were simulated, giving a total of 360 individual simulations.

The year 2014 has been chosen as a reference year in this study for pollutant concentrations as it provides a recent annual baseline to investigate the interaction between trees and the atmosphere. Although excluded here, the investigation of this relationship over time leaves room for further research.

2.3. Description of traffic data and pollutant concentration analysis

Estimated Annual Average Daily Flows (AADF) from the Department for Transport (DfT, 2016) were used to estimate road