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Impact of trees on pollutant dispersion in street canyons: A numerical study of the annual average effects in Antwerp, Belgium

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HIGHLIGHTS

- Simulation of annual average effects of street canyon trees on local air quality
- Concentration increases of 0.2% to 2.6% for PM_{10} and 1% to 13% for EC
- Annual average effects are considerably smaller than earlier estimates
- Extensive validation of CFD results against wind tunnel data

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ABSTRACT

Effects of vegetation on pollutant dispersion receive increased attention in attempts to reduce air pollutant concentration levels in the urban environment. In this study, we examine the influence of vegetation on the concentrations of traffic pollutants in urban street canyons using numerical simulations with the CFD code OpenFOAM. This CFD approach is validated against literature wind tunnel data of traffic pollutant dispersion in street canyons. The impact of trees is simulated for a variety of vegetation types and the full range of approaching wind directions at 15° interval. All these results are combined using meteo statistics, including effects of seasonal leaf loss, to determine the annual average effect of trees in street canyons. This analysis is performed for two pollutants, elemental carbon (EC) and PM_{10}, using background concentrations and emission strengths for the city of Antwerp, Belgium. The results show that due to the presence of trees the annual average pollutant concentrations increase with about 8% (range of 1% to 13%) for EC and with about 1.4% (range of 0.2 to 2.6%) for PM_{10}. The study indicates that this annual effect is considerably smaller than earlier estimates which are generally based on a specific set of governing conditions (1 wind direction, full leafed trees and peak hour traffic emissions).

1. Introduction

The past decades have been characterized by an intense urbanization. The interest in the urban living environment is therefore increasing with an important focus on air quality. Densely populated city centers have a road network of which a significant fraction consists of so called street canyons, in which roads are sided by continuous building facades. Traffic emissions in these street canyons are a large contributor to local pollutant concentrations. The effect of urban vegetation on air quality in these street canyons has been an active research field over the last few years (Amorim et al., 2013; Buccolieri et al., 2011; Gromke and Ruck, 2012; Hofman and Samson, 2014; Salmond et al., 2013; Setälä et al., 2013; Vos et al., 2013). Trees have the capacity to remove air pollutants by dry deposition, but also act as a momentum sink and influence the turbulent energy of the flow. Tree canopies can form a barrier between the street level where the traffic emissions are and the free flow above the roofs. The reduced ventilation leads to an increase in the concentration (Janhäll, 2015).

Microscale studies of these effects need 3D, building-resolving models to capture the urban environment in sufficient detail. Computational Fluid Dynamics (CFD) and wind tunnel experiments are therefore used to study the flow, turbulence and dispersion (Ahmad et al., 2005; Vardoulakis et al., 2003). Gromke et al. have investigated the effects of vegetation on the air quality in street canyon through a series of wind tunnel experiments and CFD simulations (Buccolieri et al., 2011, 2009; Gromke and Ruck, 2009, 2008, 2007; Gromke, 2011; Gromke et al., 2008; Moonen et al., 2013). They quantified the change in pollutant concentrations in the canyon for wind directions perpendicular, parallel and 45° inclined to the canyon axis and for varying street canyon aspect ratios. The experimental results have been made available through an online database (CODASC, 2008).

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As air quality policies and EU regulations are drawn up around yearly averaged concentrations, or at least some aggregation over time, it is important to assess the effect of street canyon vegetation at this level. Our objective continues from earlier findings and aims to quantify the annual average effects of trees on the air quality in street canyons. Therefore CFD simulations are presented for all wind directions at a 15° interval and a variety of trees. A range of crown porosities and deposition velocities have been investigated to cover the variety in deciduous urban trees. Further, the seasonal effects on these trees are considered. Through meteo-statistical averaging, hourly concentrations with and without canyon vegetation are summarized as annual average pollution levels. The microscale pollutant concentrations in cities are however strongly influenced by the background concentrations and all other traffic and non-traffic emissions in the complete city. For atmospheric particulate matter with a diameter of 10 μm or less, PM_{10}, and elementary carbon, EC, all these contributions have been considered and integrated in a case study of a busy urban street canyon in Antwerp, Belgium, for the year 2012.

2. Numerical model

2.1. Domain size and computational grid

Three-dimensional steady state simulations have been performed to study the air quality effect of urban trees in a street canyon using the OpenFOAM CFD package, applying the COST action 732 report as guideline for the numerical simulation setup (Franke et al., 2007).

The simulations are validated against the CODASC wind tunnel database (CODASC, 2008). The street canyon dimensions have therefore been chosen to represent the full scale street canyon the wind tunnel model represents. The buildings have a height of 18 m (H), a length of 180 m (10 H) and a width of 18 m (H). Two different street canyon widths of 18 m and 36 m have been investigated, with respective street canyon width over height ratios (W/H) of 1.0 and 2.0.

The dimensions of the computational domain consist of an approach flow region of 8 H, the street canyon region and a downwind region of 15 H. The distance from the buildings to the side boundaries of the domain as well as the top boundary is 5 H. The computational domain has been built using Gmsh (Geuzaine and Remacle, 2009), a three-dimensional finite element mesh generator. A regular hexahedral grid within 1 H distance of the street canyon is combined with an irregular grid outside this region. Inside and around the canyon, the highest resolution is requested and here a constant grid resolution of $z/H = 0.028$ and $x/H = y/H = 0.05$ is chosen with regular hexahedral cells. In order to keep the amount of cells in the domain manageable, the cell size increases by an expansion ratio of maximum 1.2 between connected cells outside this central region and the zone where the grid becomes irregular. The total computational domain consists of up to 5 million cells. It has been ensured that further increasing the resolution of the grid does not improve the results. An overview of the computational domain is given in Fig. 1. The outer region of the grid can rotate around the inner region to allow easy adaptation of the grid for variation of the angle between flow entering the domain from the inflow plane and the street canyon axis.

2.2. Boundary conditions and solution method

simpleFoam, an OpenFOAM steady-state RANS (Reynolds-averaged Navier–Stokes) solver for incompressible, turbulent flow has been used as basis to develop a solver for the air flow through vegetation. Further, through coupling with the *scalarTransportFoam* solver, the dispersion of pollutants is added as a passive scalar. A standard k–ε model has been applied as turbulence model, which is a RANS-based turbulence, linear eddy viscosity model with two extra transport equations included to describe the turbulent properties of the flow. Our use of a k–ε model including vegetation terms is here considered a sufficiently accurate model given the large variation and uncertainties in vegetation and street configurations and the need for a large number of simulations to be completed.

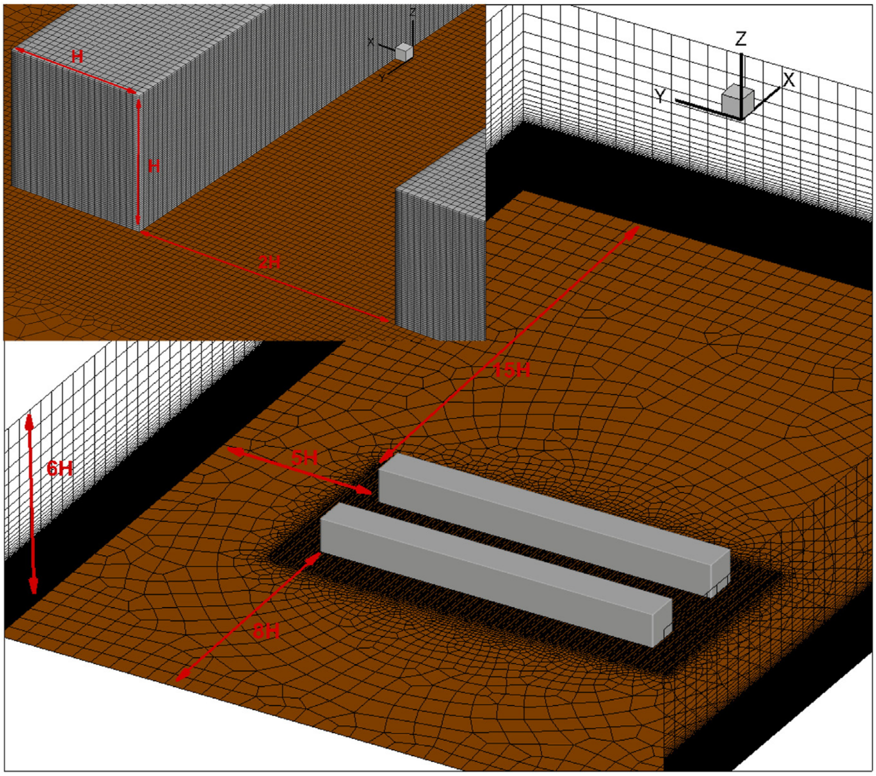

Fig. 1. Sketch of the computational domain.