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Analysis of local scale tree–atmosphere interaction on pollutant concentration in idealized street canyons and application to a real urban junction

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ABSTRACT

This paper first discusses the aerodynamic effects of trees on local scale flow and pollutant concentration in idealized street canyon configurations by means of laboratory experiments and Computational Fluid Dynamics (CFD). These analyses are then used as a reference modelling study for the extension a the neighbourhood scale by investigating a real urban junction of a medium size city in southern Italy.

A comparison with previous investigations shows that street-level concentrations crucially depend on the wind direction and street canyon aspect ratio W/H (with W and H the width and the height of buildings, respectively) rather than on tree crown porosity and stand density. It is usually assumed in the literature that larger concentrations are associated with perpendicular approaching wind. In this study, we demonstrate that while for tree-free street canyons under inclined wind directions the larger the aspect ratio the lower the street-level concentration, in presence of trees the expected reduction of street-level concentration with aspect ratio is less pronounced.

Observations made for the idealized street canyons are re-interpreted in real case scenario focusing on the neighbourhood scale in proximity of a complex urban junction formed by street canyons of similar aspect ratios as those investigated in the laboratory. The aim is to show the combined influence of building morphology and vegetation on flow and dispersion and to assess the effect of vegetation on local concentration levels. To this aim, CFD simulations for two typical winter/spring days show that trees contribute to alter the local flow and act to trap pollutants. This preliminary study indicates that failing to account for the presence of vegetation, as typically practiced in most operational dispersion models, would result in non-negligible errors in the predictions.

1. Introduction

Traffic emissions are one of the major contributors of air pollution in urban built up areas. Several numerical tools are commonly used by the air quality assessment community to investigate the effects of human activity on local concentrations. For short-range local air quality studies, sophisticated Gaussian type models are generally used, see Vardoulakis et al. (2003) for a review. These models are not appropriate for predicting flow, dispersion and the resulting concentrations in more complex scenarios such as urban junctions or industrial areas. In this case it is preferred to use building resolving models, such as Computational Fluid Dynamics (CFD). Microscale meteorological models can also be used by adjusting the domain sizes to the order of several tens of metres to a few kilometers (street canyons, city quarters). They may contain modules to simulate several atmospheric physico-chemical processes (Britter and Schatzmann, 2007).

Flow patterns inside urban street canyons result from the formation of various vortical structures that are dependent in first approximation on the street geometry: street length (L), street width (W) and building height (H). Numerous studies have extensively dealt with pollutant dispersion and flow regimes in street canyons (see for example reviews from Vardoulakis et al., 2003; Ahmad et al., 2005). Many of these previous investigations

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have shown that the case of a wind flow perpendicular to the street canyon led to the largest in-canyon pollutant concentrations. Larger levels were usually found near the ground with the leeward wall being more charged than the windward wall by a factor varying between 2 and 4. Street-level pollutant concentrations have been proven to be attributable to several factors such as wind direction and velocity, aspect ratios (W/H, L/W etc.) (e.g. Di Sabatino et al., 2008; Salizzoni et al., 2009), the presence of street intersections (e.g. Di Sabatino et al., 2007a; Soulhac et al., 2009), building roof geometry (e.g. Huang et al., 2009), building packing density (e.g. Di Sabatino et al., 2007b; Buccolieri et al., 2010) etc. However, buildings are not the only obstacles offering resistance to the airflow within urban canyons. Investigations on pollution barriers, trees and other common urban features have shown that these additional obstacles influence dispersion of traffic induced air pollution in a typical street canyon (McNabola et al., 2009; McNabola, 2010).

In particular urban vegetation, for example trees, alters the flow pattern, turbulent exchange of mass and consequently affects pollutant concentration. In the past, urban vegetation has been considered almost exclusively based on its aesthetic merit. Presently, many research studies are underway to determine the role of vegetation in urban microclimates (see for example Balczó et al., 2009; Buccolieri et al., 2009; Czáder et al., 2009; Mochida et al., 2008; Narita et al., 2008; De Maerschalck et al., 2009; Kikuchi 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 with the above roof level atmosphere. The reduction in pollutant concentration through deposition would therefore be counterbalanced by the blocking effects of trees in the street canyons, thus resulting in larger pollutant concentration as reported by Litschke and Kuttler (2008). However, even though this might be true for inert pollutants, it is not necessarily so for reactive substances such as ozone. It is therefore important to quantify the overall effect of trees on street scale pollutant concentration which is still an open research question.

Within this context, our objectives are twofold and the focus is on local scale flow and dispersion, including the street scale (less than 100–200 m) and the neighborhood scale (up to 1 or 2 km) according to the definition given by Britter and Hanna (2003).

The first objective is to extend our previous findings obtained for street canyons of aspect ratios W/H = 1 and 2 with perpendicular approaching flow (Gromke et al., 2008; Buccolieri et al., 2009) to the case of oblique wind direction. Literature addressing this case (i.e. oblique wind flow) is scarce as mentioned in the review by Ahmad et al. (2005). Similar to our previous works, in this paper we employ the Computational Fluid Dynamics (CFD) code FLUENT (2006) and wind tunnel experiments from CODASC Database (2008) to study the flow and pollutant dispersion in an idealized tree-free street canyon of aspect ratio W/H = 2 for a wind flow inclined by 45° to the street canyon axis and the effects of trees in varying aspect ratio and wind direction. The aim is to establish how important the relative effects of aspect ratio and wind direction are in the determination of the final pollutant concentration levels. This study intends also to identify a strategy for interpreting and supporting wind tunnel measurements in street canyons with tree planting by means of CFD simulations which allow us to easily visualize flow and concentration fields and give us information also where measurements are not available.

The second objective of this research is the investigation of the effect of trees on flow and dispersion in a real scenario and to show how wind tunnel experiments and model calculations can be used as background experience for a real scenario application. To this aim we apply the methodology used in the above case to simulate the effect of trees within a neighbourhood of downtown Bari (Italy) in proximity of an urban street junction. Numerical results are compared with concentration data from a monitoring station available from the Regional Agency for the Environmental Protection (ARPA). The study of different wind directions for the idealized cases forms the basis for data interpretation in real cases given the complexity of the real case as far as the building geometry and meteorology are concerned.

2. Idealized street canyon of aspect ratio W/H = 2

2.1. Description of wind tunnel experiments

The idealized street canyon case investigated in the present study consists of two parallel rows of buildings forming an urban street canyon of length $L_{full\_scale} = 180$ m, height $H_{full\_scale} = 18$ m and street width $W_{full\_scale} = 36$ m. Wind tunnel concentration measurements in a model street canyon of scale 1:150 were performed at the University of Karlsruhe/Karlsruhe Institute of Technology and publicly available from the CODASC Database (2008). Details of the experimental setup are briefly mentioned here and a complete description is available in several papers by Gromke and Ruck (2007, 2008, 2009a, 2009b).

A typical urban boundary layer with mean velocity profile exponent $\alpha = 0.30$ according to the power law formulation was reproduced as follows:

$$\frac{u(z)}{u_H} = \left(\frac{z}{H}\right)^{\alpha}, \tag{1}$$

where $u_H = 4.70\ \mathrm{ms^{-1}}$ is the wind velocity at building height H. The approaching flow was inclined by 45° to the street axis as shown in Fig. 1a. In the figure, "A" refers to the leeward wall whereas "B" to the windward wall of the street canyon.

Tree models with a pore volume fraction $P_{Vol} = 96\%$ were placed along the street canyon as shown in Fig. 1b, c. They were characterized by high and low stand densities. The first case corresponds to a trees' configuration with interfering neighbouring crowns (high density, Fig. 1b), while the second (low density, Fig. 1c) corresponds to the case with trees separated from each other by a distance equal to 0.32H (5.76 m in full scale). The height of the branch-free trunk was 1/3H (6m in full scale) as shown by the side view of Fig. 1d. To model the aerodynamic characteristics of the tree crowns, the pressure loss coefficient λ ($\mathrm{m^{-1}}$) was determined in forced convection conditions according to:

$$\lambda = \frac{\Delta p_{stat}}{p_{dyn}\ d} = \frac{p_{windward} - p_{leeward}}{(1/2)\ \rho u^2 d}, \tag{2}$$

with Δp_{stat} the difference in static pressure at the windward ($p_{windward}$) and leeward ($p_{leeward}$) of the porous obstacle in forced convection conditions, p_{dyn} the dynamic pressure, u the mean stream velocity and d the porous obstacle thickness in the streamwise direction. Measurements resulted in pressure loss coefficients of $\lambda = 200\ \mathrm{m^{-1}}$ for the tree models with pore volume fraction $P_{Vol} = 96\%$. For further information on the tree models see Gromke and Ruck (2008) and Gromke and Ruck (2009a).

Sulphur hexafluoride (SF_6) was used as tracer gas to model a constant emission rate Q_T (g/s) by four line sources each of length l (m) placed at ground level as shown in Fig. 1a. The locations of the line sources relatively to the tree rows are indicated in Fig. 1d. Concentration samples were taken a few millimetres (0.75 m in full scale) close to the leeward and windward wall and analyzed by Electron Capture Detection (ECD) yielding time-averaged (indicated as mean henceforth) concentrations c over a sampling duration of 105 s.