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ESTIMATING THE IMPACT OF STREET VEGETATION ON AIR QUALITY: A SIMPLE CASE WITH DIFFERENT TYPES AND POSITIONS OF VEGETATION

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Abstract: Urban vegetation plays an important role in urban climate and air quality. It helps to decrease pollutant concentration by means of the deposition of pollutants on the leaves, but alters the flow and dispersion processes within the streets reducing the ventilation of pollutants emitted from traffic. The first effect mitigates the urban air quality problems but the second (dynamical effect) increases pollutant concentration within the streets. To know which of these effects is dominant depends on several variables like configuration of streets and type and location of vegetation. Microscale modelling (CFD models) is a helpful tool to solve this problem. The main objective of this study is to analyse, in a simple configuration of an array of cubes, different factors like the type and position of vegetation in order to estimate the impact of street trees on the pollutant concentration. The results show that in some cases vegetation improves air quality within streets but in others make it worse.

Key words: *CFD model, deposition velocity, leaf area density, pollutant dispersion, urban vegetation.*

INTRODUCTION

Air quality is affected by urban vegetation due two main effects:

1) Aerodynamics effects. The wind within the street is modified by the vegetation, reducing, in general, the ventilation of pollutant emitted from traffic.
2) Pollutant deposition. Urban vegetation may absorb part of pollutant by means of dry deposition.

The main objective is to evaluate the impact of urban vegetation on air quality taking into account both effects, the aerodynamics and the pollutant deposition. For this purpose, CFD simulations over an array of cubes with and without vegetation are carried out. Vegetation within the street located at different height and with different leaf area densities (LAD) and deposition velocities are simulated.

MODEL DESCRIPTION AND CONFIGURATION SET-UPS

The CFD model used in this study is based on Reynolds-Averaged Navier-Stokes (RANS) equation with k-ε turbulence closure. STAR-CCM+ software is used to solve the equations. The dynamical effects of the vegetation are modelled with a sink term in the momentum equations that represents the vegetation form drag (1).

$$Su_i = -\rho LAD c_d |U| u_i \tag{1}$$

where LAD is the leaf area density, c_d is the drag coefficient of vegetation (0.2), $|U|$ is the wind speed and u_i is wind velocity in direction i.

In addition, source terms in the turbulent kinetic energy and turbulent dissipation rate equations are added ((2) and (3)). These dynamical effects of vegetation are proportional to leaf area density.

$$S_k = \rho LAD c_d \left(\beta_p |U|^3 - \beta_d |U| k \right) \tag{2}$$

$$S_\varepsilon = \rho LADc_d \left(C_{\varepsilon 4}\beta_p \frac{\varepsilon}{k}|U|^3 - C_{\varepsilon 5}\beta_d |U| \varepsilon \right) \quad (3)$$

where β_p is the fraction of mean kinetic energy converted into k by means of drag and takes a value between 0 and 1. β_d is the dimensionless coefficient for the turbulence cascade short-circuiting, that has no clear physical basis (Sanz, C., 2003). Values of β_d, $C_{\varepsilon 4}$, $C_{\varepsilon 5}$ are based on analytical expressions (Sanz, 2003; Santiago, J.L. et al., 2013; Krayenhoff, E.S., et al., 2014)

The pollutants are modelled as passive tracers. Pollutant deposition depends on the leaf area density and on the deposition velocity. It is modeled by means of a sink term in the pollutant transport equation (4).

$$S_{tr} = -LAD \cdot V_d \cdot C(x,y,z) \quad (4)$$

where V_d is the deposition velocity and C is the pollutant concentration.

The geometrical configuration is a staggered array of cubic blocks of 16 m height (H) with a packing area density (λ_p) of 0.25. The CFD simulation is carried out in a mesh resolution of 1m , which is sufficient to resolve the obstacle. Symmetry conditions are imposed in the spanwise direction, and periodic boundary conditions are imposed in the streamwise direction in order to simulate an infinite array. Horizontal periodic conditions are imposed with a pressure gradient in X-direction to maintain the wind ($\tau = \rho u_\tau^2/H_{domain}$). From it, a scaling velocity $u_\tau = \sqrt{4\tau H / \rho}$ can be derived, where ρ is the air density (kg m^{-3}). The domain height is 4H. At the domain top, zero normal derivatives are prescribed.

Fifty different vegetation scenarios are simulated in this geometrical configuration. In addition, one scenario without vegetation is also simulated. The vegetation is located at different height and the foliar layer thickness considered is 8 m. For each position of vegetation, different leaf area density and different deposition velocities are studied. (Table 1 and Fig. 1). The emissions are located close to ground.

Table 1. Description of fifty vegetation scenarios simulated. Note that for every vegetation location, all combinations of *LAD* and *Vd* are simulated (10 simulations, i.e. for every *LAD*, 5 deposition velocities).

Vegetation location	Name Vegetation Location	*LAD* (m^2 m^{-3}) (for every Veg. Loc.)	V_d (m s^{-1}) (for every Veg. Loc. and *LAD*)	u_τ (m s^{-1}) (for every Veg. Loc.)
From 0 m to 8 m	Tree 1	0.125	0.1	0.45
From 4 m to 12 m	Tree 2	0.5	0.05	
From 8 m to 16 m	Tree 3		0.001	
From 12 m to 20 m	Tree 4		0.0005	
From 16 m to 24 m	Tree 5		0	

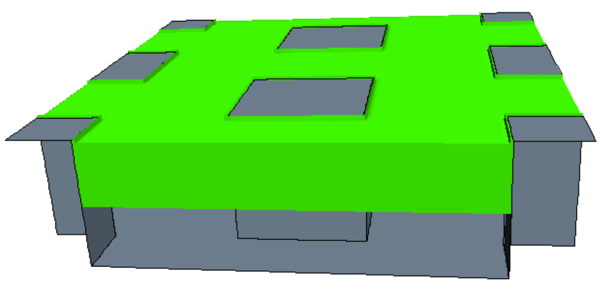

Figure 1. Example of scenario configuration (Tree 3). The vegetation is represented in green.

RESULTS

In order to determine a suitable normalization of variable, an additional simulation with a different u_τ is carried out. Wind speed and turbulent kinetic energy can be normalized with u_τ and u_τ^2. A normalized concentration (C^*) is defined as $C^* = C\, u_\tau\, H^2/Q$, where Q is the total emission per time. Figure 2 shows the vertical profile of horizontal average of normalized concentration for two different scenarios with the same vegetation location (Tree 3), LAD (0.125 $m^2\, m^{-3}$) and V_d/u_τ. We can see that for normalized concentration (C^*) cases with the same vegetation location, the same LAD and the same V_d/u_τ are equivalent.

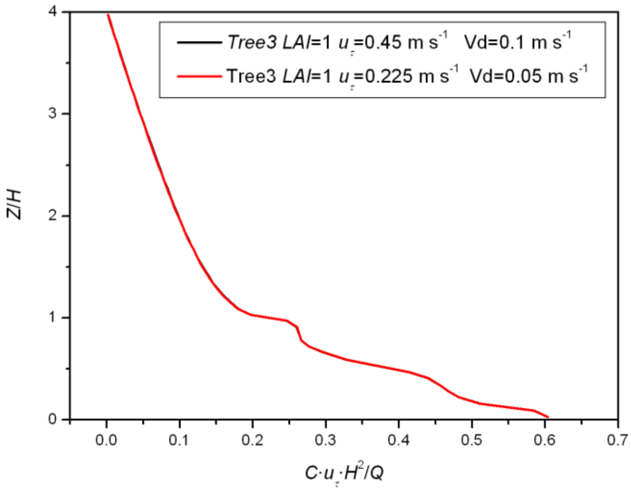

Figure 2. Horizontal average profiles C^* for two different scenarios with the same vegetation location (Tree 3), LAD (0.125 $m^2\, m^{-3}$) and V_d/u_τ.

In order to quantify the impact of vegetation type on pollutant concentration, for each case the concentration is normalized by the concentration obtained for the same scenario but without vegetation. Then, a value above one (below one) indicates that the concentration is increased (decreased) by the presence of vegetation. Firstly, the horizontal average concentration at 2.5 m (z/H = 0.16) is analysed. As expected, for each case higher the deposition velocity, lower the concentration average is. Figures 3-5 show the values for three different vegetation locations: Tree2 (top of vegetation is below buildings), Tree3 (top of vegetation is equals to building height) and Tree4(top of vegetation is above buildings).

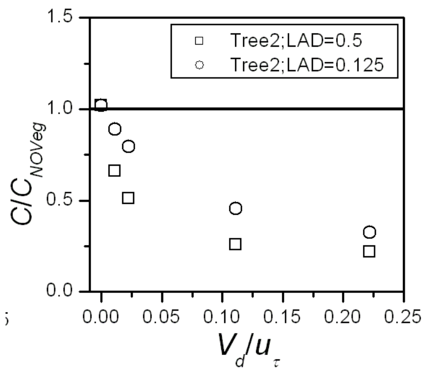

Figure 3. Horizontal average concentration at 2.5 m (z/H = 0.16) for Tree2 normalized by the concentration for the same case but without vegetation.

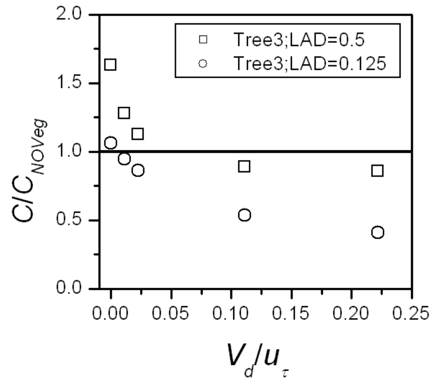

Figure 4. Same as Figure 3 but for Tree3.

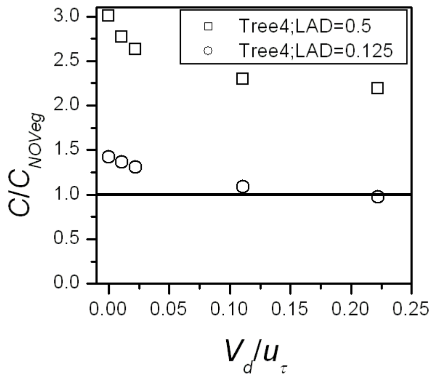

Figure 5. Same as Figure 3 but for Tree4.

In terms of average concentration at this height, the vegetation below the buildings (Tree 2) reduces the concentration even for low deposition velocities. In addition, for higher LAD, this reduction is higher due to the higher deposition. This means that the vegetation at these heights induces a lower aerodynamics effect in comparison with the deposition. Also, we have to take into account that the vegetation is closer to the pollutant source where the concentration is higher. For the vegetation at the top of the canopy (tree 3), the cases with LAD = 0.5 m^2m^{-3} the vegetation induces a reduction of ventilation and only for higher deposition velocities the average concentration at this height is reduced. For the cases (Tree 3) with LAD = 0.125 m^2m^{-3}, the aerodynamics effects are lower and the reduction of the average concentration can be found for lower deposition velocities. However, for the cases where the vegetation exceed the building height (Tree 4) the reduction of ventilation is higher enough (even for the lower LAD scenarios or high deposition velocities) to improve the air quality in terms of average at 2.5 m. However, the vegetation modifies the flow field and the distribution of pollutants and the effects cannot be analysed only in terms of average values. The maxima of concentration are displaced and their values can change in a different way of average concentrations. As for the average values, when the vegetation is higher than buildings, the maximum of concentration are higher than for the other cases. However, the re-distribution of pollutant concentration inducing by the presence of vegetation produces, in general, an increase of the maximum concentration for each case respect to the no-vegetation case. In some scenarios with similar average concentration to the corresponding no-vegetation case, higher maximum concentration at this height is found for vegetation cases. Figure 6 shows this fact for Tree 3. In certain sense, the vegetation induces more heterogeneities in the pollutant distributions. Vegetation type and location changes the flow field (ventilation of the streets) and pollutant distribution within the street changing not only the average concentration but also the maximum values and positions. This fact is illustrated in Figure 7. Pollutant concentration distribution in a vertical plane in the middle of the street is shown for tree 2, 3 and 4 with LAD = 0.5 m^2m^{-3}, $Vd/u\tau = 0.02$ (e.g. Vd = 0.01 ms-1 and uτ = 0.45 ms-1).

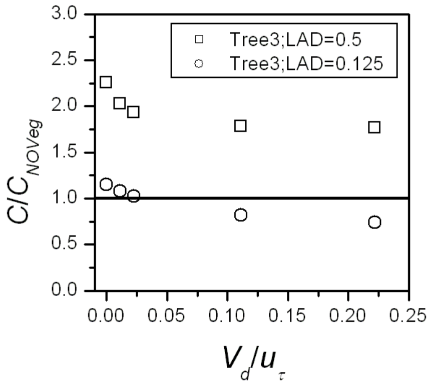

Figure 6. Same as Figure 3 but for maximum concentration at 2.5 m (z/H = 0.16).

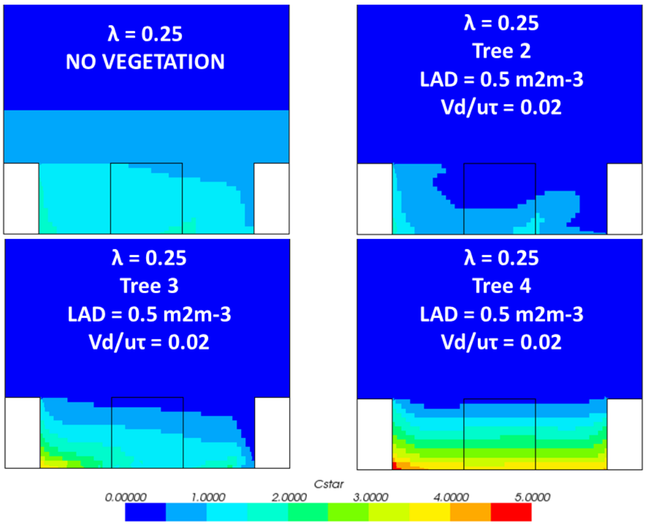

Figure 7. Concentration distribution in a vertical plane in the middle of the canyon for different locations of vegetation.

CONCLUSIONS

From the results, we can conclude that the three features of the vegetation (leaf area density, deposition velocity and position) are important factors to be taken into account to determine whether the street trees induce a reduction or an increase of the concentration of pollutant emitted from traffic respect to the case without vegetation. For example, trees above the building height reduce the ventilation and increase the concentration in the whole canopy.

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