H13-263
CFD-MODELING OF COMPLEX PLANT-ATMOSPHERE INTERACTIONS: DIRECT AND INDIRECT EFFECTS ON LOCAL TURBULENCE

Bart De Maerschalck[1], Bino Maiheu[1] , Stijn Janssen[1] and Jean Vankerkom[1]

[1]VITO, Dep. Environmental Modelling, Boeretang 200, 2400 Mol, Belgium

Abstract: It is well known that plants are capable of capturing pollutants, both gas species and particulate matter, by absorption through the stomata or deposition on the leaf surface. From this perspective a wide interest, scientific, political and even public, gained in the practical use of vegetation to improve local air quality. However, it is true that the complexity of the plant-atmosphere interaction mechanisms is often underestimated. It turns out that except for deposition and absorption processes, local air quality is mainly affected by the aerodynamic plant-atmosphere interactions, which are not always straightforward to understand. In this paper it is demonstrated, using realistic model runs, that vegetation can both directly or indirectly enhance turbulence. On the other hand, for specific meteorological conditions or geometries, vegetation can decrease turbulence kinetic energy and act as a diffuser breaking down turbulent eddies as well. Since both advection and turbulent diffusion have a direct effect on pollutant dispersion, these complex interactions can strongly affect local air quality.

***Key words:** Key CFD-based air quality modelling, vegetation interactions, vegetation barriers.*

INTRODUCTION
It is well known that plants are capable of capturing pollutants, both gas species and particulate matter, by absorption through the stomata or deposition on the leaf surface. From this perspective a wide interest, scientific, political and even public, has been gained in the practical use of vegetation to improve local air quality. Different models on different scales are developed to estimate the deposition and absorption. Different techniques to measure the total absorbed and deposed amount of pollution are available or under development as well. However, when one tries to measure the net effect of this absorption processes on the local air quality by means of accurate atmospheric concentration measurements, it turns out to be very difficult to measure significant improvements and under certain conditions, vegetation can even locally have negative effects on the air quality. This is due to the fact that the complexity plant-atmosphere interaction is often underestimated. It turns out that apart from deposition and absorption processes, local air quality is mainly affected by the aerodynamic plant-atmosphere interactions.

Computational fluid dynamic (CFD) models are capable of describing in detail these effects by solving numerically the physical conservation laws of mass, momentum and energy, or the so called Navier-Stokes equations. Presented is a CFD-based air quality model Envi-met. In this model vegetation is modelled as a porous element giving an extra sink term in the momentum equations and additional sink/source terms for the turbulent kinetic energy and energy dissipation rate. Also in the dispersion model for different pollutants the effect of absorption and deposition is modelled by a sink term with a dynamically computed deposition velocity depending on the plant physiological condition of vegetation and characteristics of the pollutant.

It is well understood that plants act as porous barriers. This barrier slows down the wind depending on the size, type and porosity of the plant. However, less is known on the spatial range of this effect and how this is dependent on the atmospheric turbulence. Also the complex interaction of vegetation and turbulent energy is less understood. It will be demonstrated using realistic model runs that vegetation can both directly or indirectly enhance turbulence, but on the other hand for specific meteorological conditions or geometries, vegetation can decrease turbulence kinetic energy and act as a diffuser braking down turbulent eddies as well. Since both advection and turbulent diffusion have a direct effect on pollutant dispersion, these complex interactions can strongly affect local air quality.

THE ENVI-MET MODEL
Envi-met was originally build by Prof. M. Bruse, University of Mainz, and has been further developed in collaboration with the Flemish Institute For Technological Research. Envi-met is a three-dimensional CFD-based micro climate model coupled with a simple soil model and radiative transfer model (Samaali, Courault *et al.* 2007), and with an air quality model incorporated. The numerical model is a finite difference scheme on a uniform mesh. Typical grid resolution varies between 0.5 to 10 meters with the possibility to refine gradually in the vertical direction in order to capture steep gradients in wind en turbulence profiles close to the lower boundary. For a full description of the model the reader is referred to the work of Bruse (Bruse and Fleer 1998; Bruse 2004; Bruse 2004; Bruse 2007; Bruse 2007). In the next sections a brief overview of the different processes will be presented.

Atmospheric model
The main module of the model is the three-dimensional atmospheric CFD model which calculates in each point of the mesh the meteorological conditions like wind, temperature, humidity and turbulent kinetic energy. The mean wind pattern is defined by the non-hydrostatic incompressible Navier-Stokes equations. Since the Reynolds Averaged Navier Stokes (RANS) equations are implemented, the turbulence is modelled by a 1.5 order turbulence model. Based on the work of Mellor (Mellor and Yamada 1975) two additional prognostic variables, the local turbulence (E) and its dissipation rate (ε) are added to the model. Envi-met also has incorporated a flux balance model, both for short wave and long wave radiation. In order to be able to incorporate the influence of different soils on radiation, temperature and humidity, the model is coupled with a simplified soil model which computes soil temperature and water content. Vegetation is modeled as a porous element

offering resistance to the flow. This resistance is added as a local source to the momentum equations and is parameterized following Liu (Liu, Chen *et al.* 1996) and Yamada (Yamada 1982):

$$S_i = c_d \, LAD \, V \, u_i \; . \tag{1}$$

with cd=0.2 the plants mechanical drag coefficient, V the local wind speed, ui the wind component in the i-th direction and LAD the local leaf area density. Figure 1 shows the reduction in wind speed behind a vegetation barrier along an elevated motorway computed by Envi-met, from the Dutch Air Quality Innovation Project (Erbrink, Hofschreuder *et al.* 2009). The ambition of the programme was to come up with a strategy to improve local air quality in the vicinity of motorways and so called hot spots. One of the seven branches of the project is the investigation, both by means of in situ measurements and by modelling, of the effects of line vegetation along a motorway. Figure 2 compares the Envi-met model results with the field measurements. Wind speeds have been measured by means of anemometers at different location (between the motorway and vegetation, next to the highway in the open field and 10 meters behind the vegetation) and at different heights. The plots in Figure 2 compare the modelled wind profiles (full lines) at the different location with the available measurement data (dots with error bars). The red lines and dots are the measurements and modelled profiles in the open field. The green lines and dots are those in front and behind the vegetation barrier.

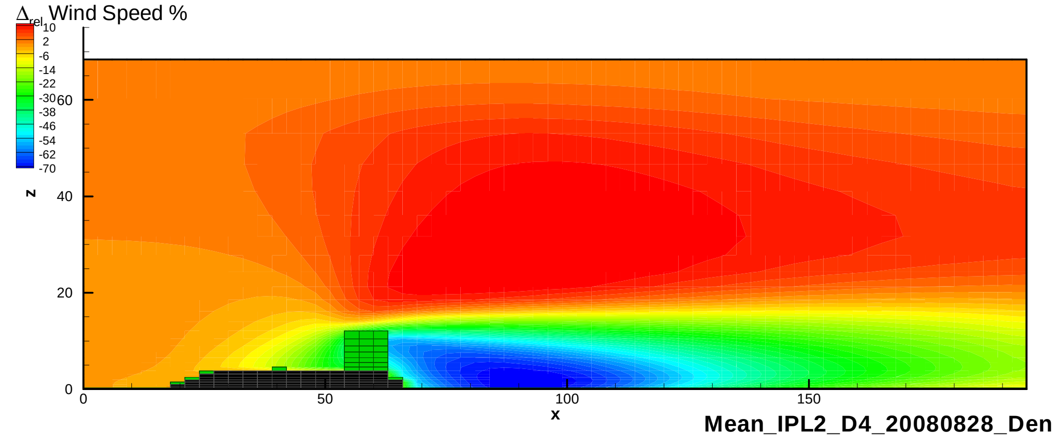

Figure 1: Wind speed reduction behind a vegetation barrier along an elevated motorway (Envi-met modelling of A5O near Valburg, The Netherlands, within the Dutch Air Quality Innovation Project, (Erbrink, Hofschreuder *et al.* 2009))

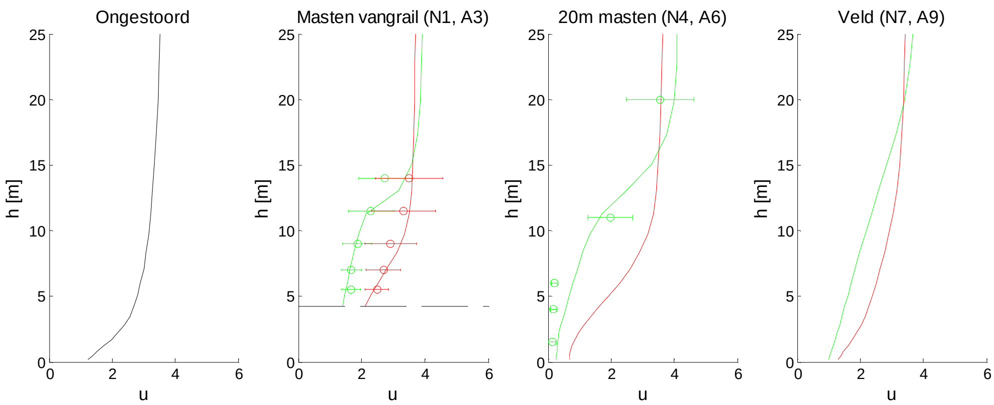

Figure 2: Wind profiles measured and modelled at different locations: Undisturbed flow, right in front of the vegetation, 10 meters behind the vegetation, 80 meters behind the vegetation (Erbrink, Hofschreuder *et al.* 2009).

The effect of the vegetation on the local turbulence (E) and its dissipation rate (ε) is again modeled by two additional source terms added to the E-ε – turbulence model. According to Liu (Liu, Chen *et al.* 1996) and Wilson (Wilson 1988):

$$Q_E = (V^2 - 4E)\, c_d \, LAD \, V \; , \tag{2}$$

$$Q_\epsilon = (1.5\, \frac{V^2}{E} - 6)\, c_d \, LAD \, V \, \epsilon \; . \tag{3}$$

See Bruse (Bruse 2004) for a more detailed description of the turbulence model.

It is well understood that any type of barrier that obstructs the free flow is a cause of mechanical drag. However little is known on the fact that due to the fine structure of the branches and leaves or needles, a vegetation barrier can act as a diffuser as well and stabilize locally the air flow. To understand this, consider for a moment the *E*-*ε* – turbulence model:

$$\frac{\partial E}{\partial t} + u_i \frac{\partial E}{\partial x_i} = K_E \frac{\partial^2 E}{\partial x_i^2} + Pr - Th + Q_E - \epsilon \ , \quad (4)$$

$$\frac{\partial \epsilon}{\partial t} + u_i \frac{\partial \epsilon}{\partial x_i} = K_\epsilon \frac{\partial^2 \epsilon}{\partial x_i^2} + c_1 \frac{\epsilon}{E} Pr - c_2 \frac{\epsilon^2}{E} - c_3 \frac{\epsilon}{E} Th + Q_\epsilon \ , \quad (5)$$

with *Pr* the mechanical production term, *Th* the thermal stratification term and Q_E and Q_ε the source terms for vegetation as given in Eq. (2) and **Erreur ! Source du renvoi introuvable.**. *Pr* is the mechanical production term for the turbulence caused by shear stresses, e.g. at the top of a vegetation barrier where a steep velocity gradient can be observed due to the strong speed reduction in the vegetation crown.

Notice from Eq. **Erreur ! Source du renvoi introuvable.** that Q_E can have both a positive or a negative sign. This means that inside the vegetation crown turbulent kinetic energy can either be generated, but can be absorbed as well. The sign of this term depends on the ratio $\frac{V^2}{4E}$. If this ratio is bigger than one then inside the vegetation extra turbulence is created, if smaller than one, the vegetation crown is acting like a diffuser, stabilizing locally the atmosphere. This is when the mean wind speed is low, but the turbulent kinetic energy is high. One can think of a typical street canyon situation: inside the street canyon the local wind speed is low. However, the roughness of the urban environment and sharp edges of roofs and other blunt bodies create a lot of mechanical turbulence. Notice from Figure 1 and 2 above that inside the vegetation crown the wind speed is strongly reduced anyway. Figure 3 shows a cross section of the turbulence field behind a vegetation barrier. One can clearly distinct a strong production of turbulent kinetic energy due to a strong shear layer initiated at the top of the trees, but also a zone of reduced TKE due to the absorption of turbulent energy inside the vegetation. However, the effect of vegetation on the local turbulence field, which will directly affect the local air quality, is strongly dependant to the meteorological conditions.

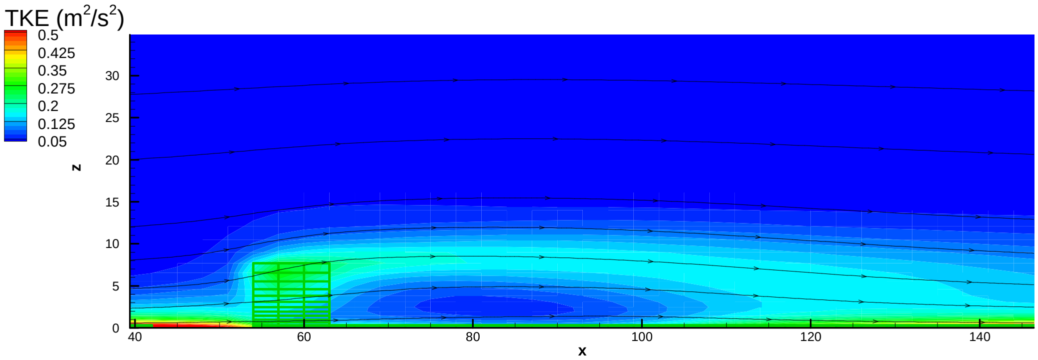

Figure 3: Effect of vegetation on the turbulent kinetic energy. Notice both production of TKE due to a strong shear layer coming from the top of the vegetation barrier, but also a zone of reduced TKE behind the barrier.

It has been stated before that the effect of the vegetation on the turbulence field, directly influences the local air quality in case of a near source like a traffic road. This is demonstrated in Figure 4 where two different days of the above mentioned measurement campaign have been modelled. In the top plot the vegetation leads meanly to a local increase of PM_{10}, while in the lower plot of Figure 4 a slight improvement behind the same vegetation barrier can be noticed.

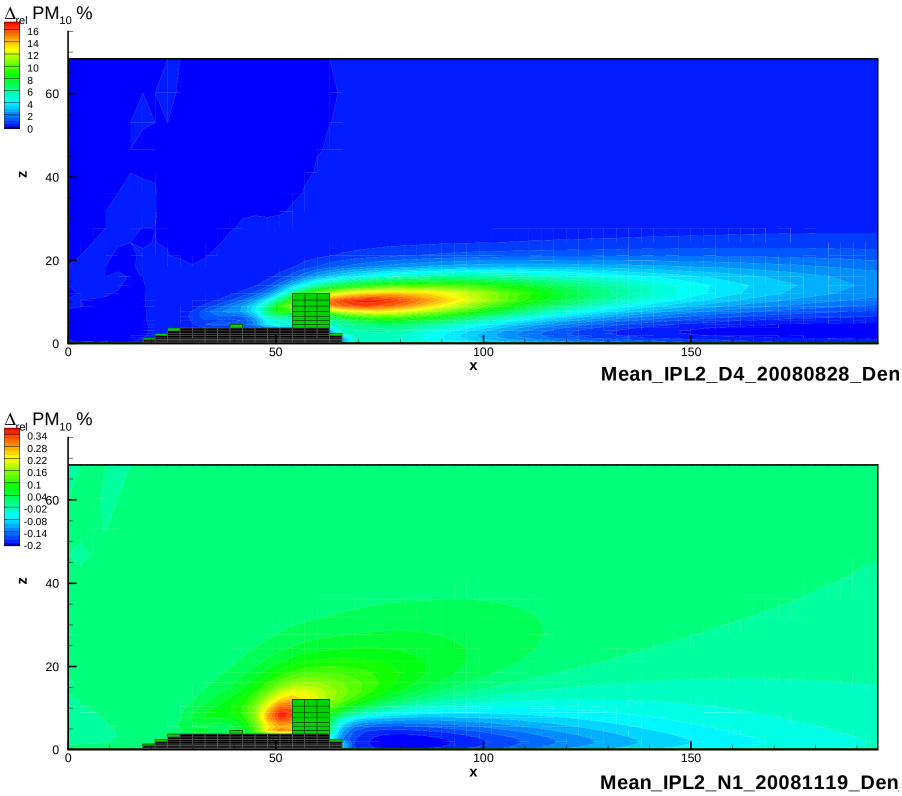

Figure 4: Effect of the vegetation on the local air quality for one of the modelled days (top) and one of the modelled nights (bottom) (Erbrink, Hofschreuder *et al.* 2009).

CONCLUSIONS

The complexity of the mechanisms of vegetation effecting the local air quality are often underestimated. Due to the porosity and the fine structure of branches and leaves, the body of the vegetation can both introduce extra mechanical turbulence, but can also absorb turbulent kinetic energy, while the strong wind speed reduction around the vegetation causes strong shear stresses and therefore extra turbulence. Model analysis shows that these processes strongly depend on the local meteorological conditions. Better understanding of these mechanisms will give better insight in the effects of vegetation on local air quality.

REFERENCES

Bruse, M. (2004) "ENVI-met 3.0 updated model overview.", http://www.envi-met.com

Bruse, M. (2004) "ENVI-met implementation of the Jacobs A−gs Model to calculate the stomata conductance." http://www.envi-met.com

Bruse, M. (2007) "ENVI-met implementation of the gas / particle dispersion and deposition model PDDM." http://www.envi-met.com

Bruse, M. (2007), Particle filtering capacity of urban vegetation: A microscale numerical approach. *Berliner Geographische Arbeiten* 109, 61-70.

Bruse, M. and H. Fleer (1998), Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model. *Environmental Modelling & Software* 13.

Erbrink, H., P. Hofschreuder, *et al.* (2009), *Vegetatie voor een betere luchtkwaliteit: Perceel II – A50 Valburg*, Stadsregio Arnhem Nijmegen – KEMA – WUR – Alterra – Integralis PP BV – VITO,

Liu, J., J. M. Chen, *et al.* (1996), E-epsilon modelling of turbulent air flow downwind of a model forest edge. *Boundary-Layer Meteorology* 77(1), 21-44.

Mellor, G. L. and T. Yamada (1975), : A simulation of the Wangara atmospheric boundary layer data. *Journal of Atmospheric Science* 32, 2309-2329.

Samaali, M., D. Courault, *et al.* (2007), Analysis of a 3D boundary layer model at local scale: Validation on soybean surface radiative measurements. *Atmospheric Reseach* 85, 183-198.

Wilson, J. D. (1988), A second order closure model for flow through vegetation. *Boundary Layer Meteorology* 42, 371-392.

Yamada, T. (1982), A numerical model study of turbulent airflow in and above a forest canopy. *Journal of the Meteorological Society of Japan* 60, 439-454.