CFD-modelling of complex plant-atmosphere interactions

Direct and indirect effects on local turbulence

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It is true that complexity of plant-atmosphere interactions are often underestimated, especially when dealing with single trees in a complex environment. On the one hand vegetation is capable of absorbing gas pollutant through the stomata and capturing particulate matter on the leaf surface; and hence the vegetation is purifying the air. However, on the other hand the presence of vegetation is strongly affecting the wind-field and turbulence intensity, which directly influences the dispersion of pollutants. Because of the complex structure of the vegetation, the turbulence can be influenced in different ways, and therefore it can have some unexpected effect on local air quality.

The Envi-met model

Envi-met was originally build by Prof. M. Bruse, University of Mainz, and has been further develop in collaboration with the Flemish Institute For Technological Research. The main module of the model is the three-dimensional atmospheric CFD. 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. 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.

Aerodynamic resistance

Vegetation is modelled as a porous element offering resistance to the flow. This resistance is added as a local sink to the momentum equations and is parameterized following Liu [8] and Yamada [9]:

$$S_i = c_d \, LAD \, |V| \, u_i$$

with c_d=*0.2* the plants mechanical drag coefficient, V the local wind speed, u_i 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 motor way computed by Envi-met, from the Dutch Air Quality Innovation Project (IPL), while Figure 2 compares the Envi-met model results with the field measurements.

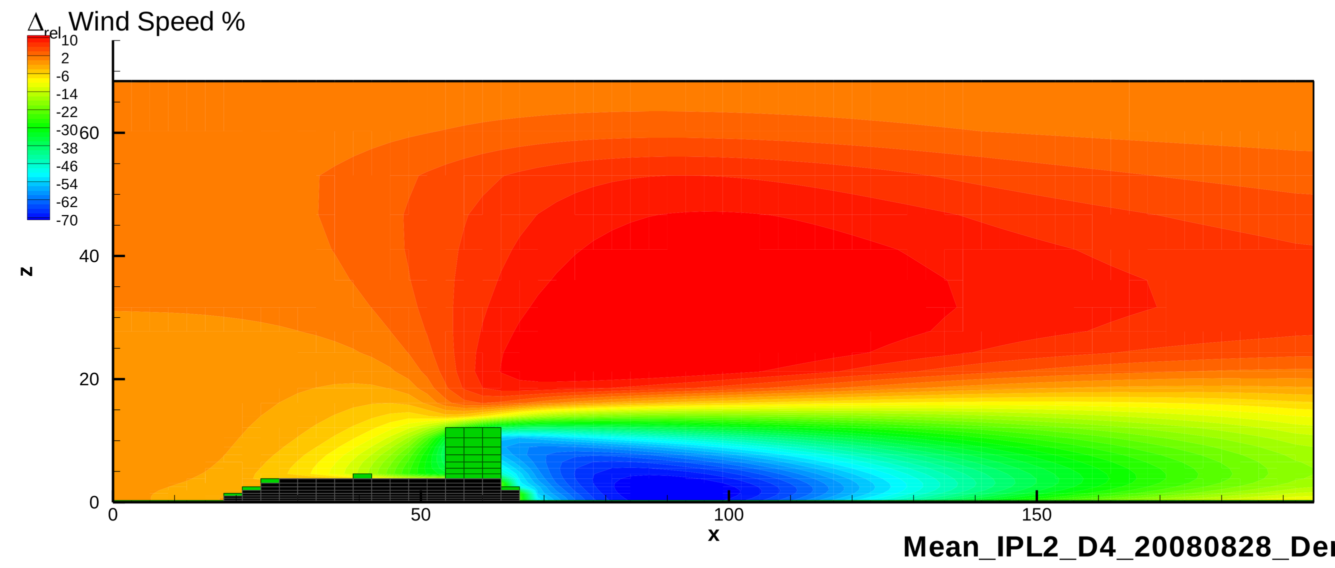

Fig. 1. Wind speed reduction behind a vegetation barrier along an elevated motor way (Envi-met modelling of A5O near Valburg, The Netherlands, within the Dutch Air Quality Innovation Project)

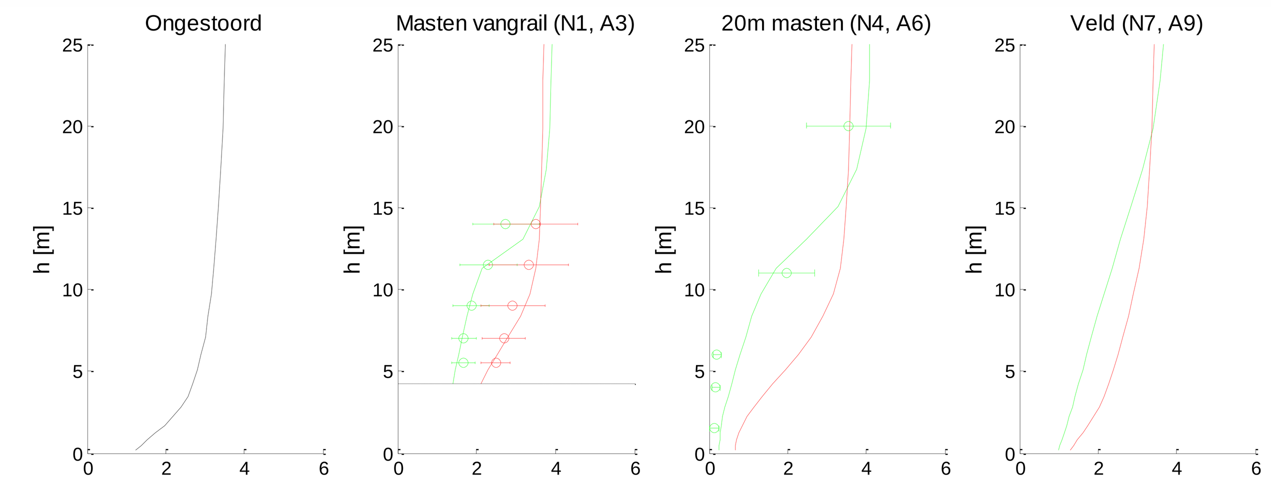

Fig. 2. Wind profiles measured and modelled at different locations: Undisturbed flow, right in front of the vegetation, 10 meters behind the vegetation, 80 meters behind the vegetation. (red lines and dots: no vegetation barrier, green: with vegetation barrier)

Turbulence effects

The reduction in wind speed will generate additional turbulence due to shear stresses. For a vegetation barrier this will be typically initiated at the top of the trees, but for single trees or when there is low leaf density between the ground and the crown, also there shear stresses will produce mechanical turbulence.

Additionally, in the turbulence model an extra sink/source term is added when in order to model the direct influence of the complex structures of branches and leaves:

$$Q_E = (V^2 - 4E)\, c_d \, LAD \, V \,,$$

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

with Q_E the addition sink/source term for the turbulent kinetic energy and Q_ε for the dissipation of turbulent energy. Notice that these terms can both be positive and negative. Therefore, the foliages can both generate additional turbulence, but can act as a diffuser as well and have a local stabilizing effect, depending on the ratio local wind speed and turbulent energy. This is illustrated in Figure 3.

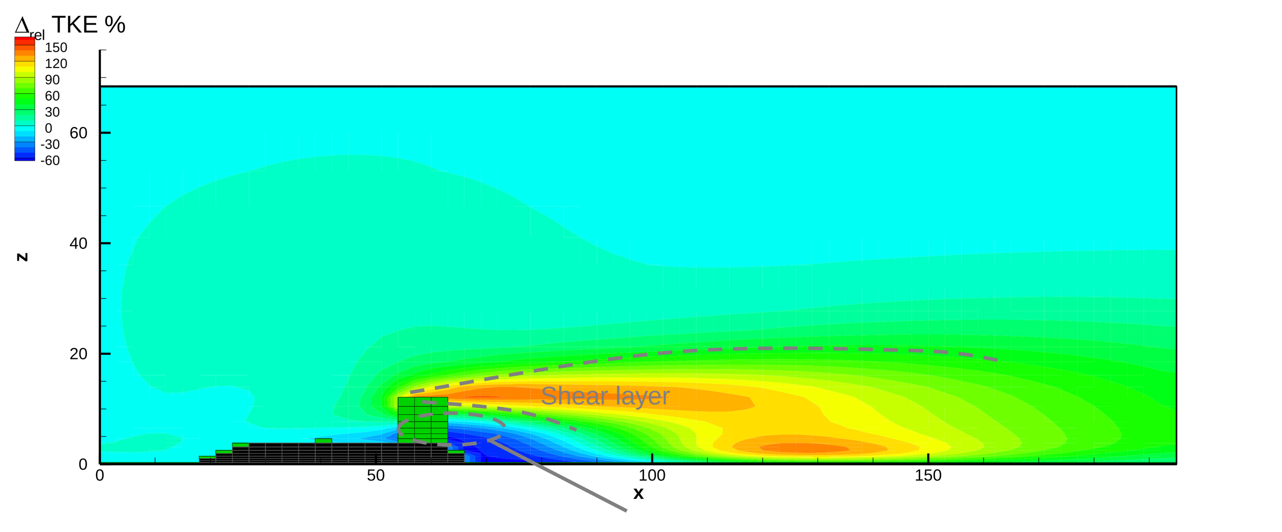

Fig. 3. Effect of a vegetation barrier on the local turbulent kinetic energy.

Since turbulence is effecting directly the dilution of locally emitted pollutants, the effect of a vegetation barrier along a freeway will depend on the local meteorological conditions. In case of high wind speeds, but low turbulent kinetic energy, the vegetation will generate extra turbulence both by generating a strong shear layer, but also directly through the crown of the vegetation. On the other hand, on days with low wind speed, but relatively high turbulent kinetic energy, the crown will act as a stabilizer and reduce dilution rates. The latter one is also something typically what happens in street canyons with vegetation in it. The effect of the atmospheric stability on the change in turbulent kinetic energy and the development of a traffic related pollution plume along a freeway with a single vegetation barrier is also illustrated in Figure 4

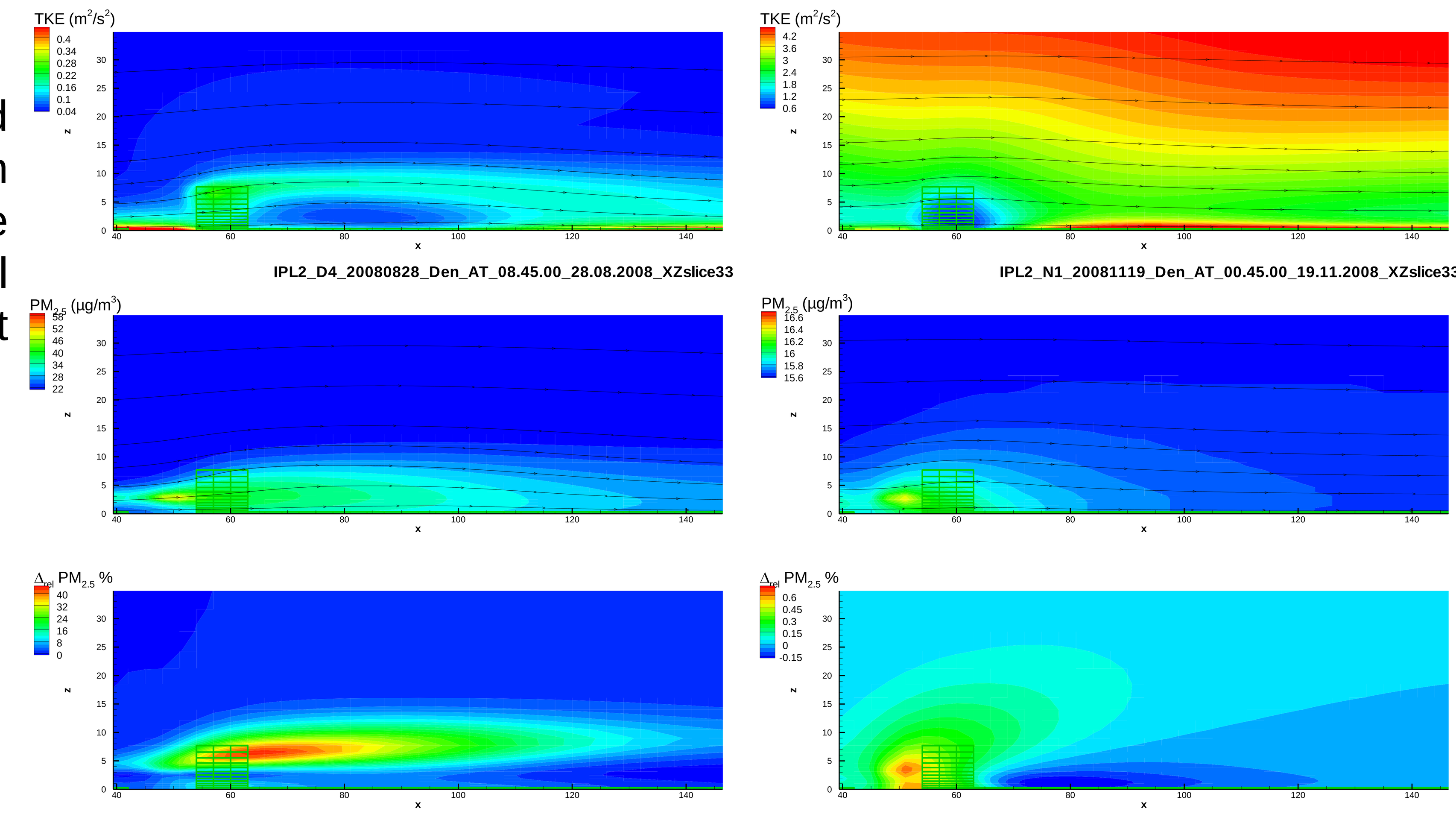

Fig. 4. Effect of a vegetation barrier on the local turbulent kinetic energy and the pollution plume of a freeway under different atmospheric conditions

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