CFD SIMULATIONS OF THE IMPACT OF A LINE VEGETATION ELEMENT ALONG A MOTORWAY ON LOCAL AIR QUALITY

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Abstract: In the paper a CFD-based micro scale air quality model called ENVI-met will be presented. ENVI-met distinguishes itself from other CFD-models due the implementation of a detailed vegetation model which describes the interaction of local vegetation, not only on the wind field, but also on the thermodynamic processes and the diffusion and deposition of gases and particulate matter. This makes the model particularly suitable for a recent research programme initiated by the Air Quality Innovation Project (IPL), founded by the Dutch Ministry for Transport, Public Works and Water Management (Rijkswaterstaat) and the Ministry of Housing, Spatial Planning & the Environment (Ministry of VROM). One of the seven branches of the IPL-project is to investigate both by measurements and modelling the effect of line vegetation along a motorway on local air quality. Recently the model results have been compared to a first measurement campaign.

Key words: *CFD, micro scale air quality modelling, vegetation, deposition.*

1. INTRODUCTION

Computational Fluid Dynamics or CFD-based air quality models have the capability to describe the local atmospheric conditions over a complex domain in a detailed way. This makes them particularly useful for small scale air quality modeling in complex areas like an irregular street canyon with vegetation objects, multiple emission sources and chemical reactions.

ENVI-met is such a CFD-model. It was originally designed as a micro-climate model by Prof. M.Bruse, University of Mainz, Germany (1998, 2004, 2007). Later it has been extended with an air quality module for both quasi inert gases and particulate matter. Recently, by the Flemish Institute for Technological Research (VITO) the air quality module has been extended with a chemical model for the photo-chemical reactions of ozone and nitrogen oxides. ENVI-met has implemented an extended vegetation module which not only describes the effect on the wind-field and turbulent kinetic energy, but also describes the thermodynamic effects of the vegetation on the ambient air, as well as the effects on the diffusion and deposition of gases and particulate matter. For this, ENVI-met has implemented a plant physiologic model which calculates the stomata resistance based on the local radiation, leaf surface temperature, the ratio of leaf- to ambient air CO_2-concentrations and water content. For the latter one the CFD-model is coupled to a simplified soil model as well.

Recently the model has been used within the framework of the Dutch Air Quality Innovation Program (IPL), initiated by the Dutch ministries for Transport, Public Works and Water Management (Rijkswaterstaat) and for Housing, Spatial Planning and Environment (Ministry of VROM). The ambition of the programme is 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 braches of the project is the investigation, both by the means of in situ measurements and by modelling, of the effect of line vegetation along a motorway. In this framework, recently the model results have been compared to a first measurement campaign which was executed before in the summer of 2006 along the A50 close to the village of Vaassen, The Netherlands. The results will be published soon by the Dutch Ministry. A brief overview of the results are described in the paper.

2. THE 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. ENVI-met is a thee-dimensional CFD-based micro climate model coupled with a simple soil model and radiative transfer model (Samaali *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 1 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 ground. For a full description of the model the reader is referred to the work of Bruse (1998, 2004, 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 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 (1996) and Yamada (1982):

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

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

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

$$Q_\varepsilon = (1.5V^2 - 6\varepsilon)c_d LAD\ V \tag{3}$$

See Bruse (1998, 2004, 2007) for a more detailed description of the turbulence model.

Air quality model

ENVI-met has multiple dispersion equations implemented to solve for different gases and particulate matter simultaneously. In case of nitrogen oxide, ozone and nitrogen dioxide, the advection diffusion equations are coupled by a non-linear chemical reaction term for the chemical reaction:

$$NO + O_3 \leftrightarrow NO_2 + O_2 \tag{4}$$

The reaction is sensitive to ambient temperature (Seinfeld and Pandis, 2006) and short wave radiation (Berkowicz and Hertel, 1989), which are both calculated by ENVI-met.

ENVI-met has implemented an extended vegetation module which calculates the effect of the vegetation both on the dispersion and deposition of gases and of particulate matter. The dispersion is indirectly influenced by the additional source terms in the momentum equations and the turbulence model. The deposition is influenced directly by calculating the deposition velocities in the vegetation elements based on a resistance scheme (Pandis and Seinfeld, 2006), with for gases:

$$v_d = \frac{1}{r_a + r_b + r_t} \tag{5}$$

and for particulate matter:

$$v_d = \frac{1}{r_a + r_b + r_a r_b v_s} + v_s \tag{6}$$

with r_a the aerodynamic resistance, r_b the laminar sublayer resistance and v_s the settling speed (only for particulate matter). r_t is the additional surface resistance which is the sum of the stomata resistance and the mesophyl resistance. These are dependant on the type and condition of the plant, the meteorological conditions and also strongly dependant on the type of gas for which the deposition speed is calculated. For the stomata resistance the plant physiologic A-g_s model of Jacobs (Bruse, 2004) has been implemented. According to Braden (1982) the aerodynamic resistance r_a is a function of the leaf geometry and the local wind speed inside the vegetation canopy:

$$r_a = A\sqrt{\frac{D}{V}} \tag{7}$$

With A a plant parameter set to 87 $s^{1/2}m^{-1}$ for conifers and grasses and 200 $s^{1/2}m^{-1}$ for conifers. D is the typical leaf length ranging from 0.02 m for conifers up to 0.5 m or more for tropical plants (Schilling, 1990). For a detailed description of the sublayer resistance and the settling speed see Seinfeld and Pandis (2006) or Bruse (2007).

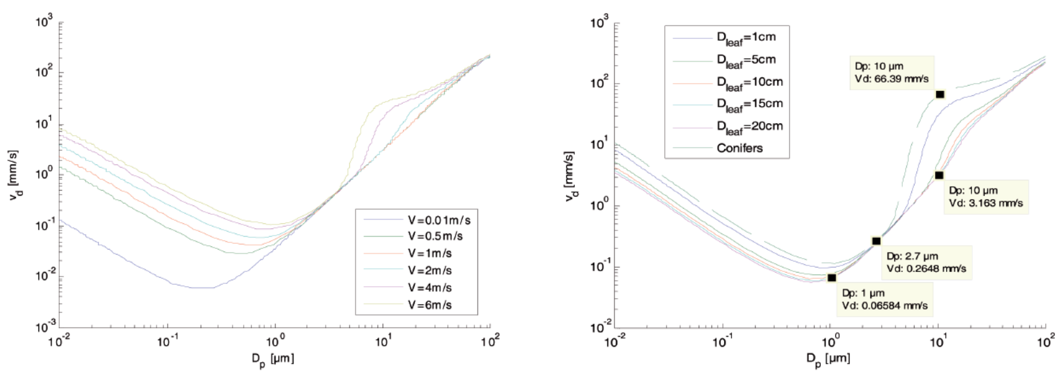

Figure 1. Deposition velocity as function of the particle size for different local wind speeds inside the vegetation canopy (leaf size = 0.15m, left) and different leaf sizes (wind speed = 2 ms^{-1}, right).

For particle matter, deposition speed strongly depends on the particles size. Figure 1 shows the deposition speed as function of the particle size for different local wind speeds inside the vegetation canopy and for different typical leaf sizes. At the moment, in the model for particulate matter the whole range of particle sizes is distributed over two discrete size bins. One for coarse particles, i.e. all particles with a diameter between 2.5 and 10 μm, and a fine bin, D_p < 2.5 μm. For each bin a mean particle diameter of 3.75 μm for the coarse and 0.75 μm for the fine bin is defined. In the future the model will be extended to a continuous size distribution which will incorporate the chemical and physical reactions of the particles.

3. THE AIR QUALITY INNOVATION PROJECT

The air quality innovation project (IPL), initiated by the Dutch ministries for Transport, Public Works and Water Management (Rijkswaterstaat) and for Housing, Spatial Planning & the Environment (Ministry of VROM), aims to find a concrete strategy in order to improve the air quality in the vicinity of motorways and so called hot spots. One of the seven branches of the project is the investigation, both experimentally and numerically, of the effect of vegetation along the motorway. A first measurement campaign has been set up along the A50 close to Vaassen, The Netherlands, from August till October 2006 by the Dutch Energy Research Centre (ECN). During this period nitrogen oxides and fine dust are measured at different lengths (10, 45 and 90 *m*) downwind from the high way in two fields next to the A50, one without vegetation and one separated from the motorway by line of trees and bushes of about ten meters high and wide. Figure 2 shows the area of the measurement campaign with the lines along which the measurements were taken. The white box indicates the model domain for the model. Unfortunately, because of exceptional meteorological conditions that summer, during all the measurement campaign there were only five days that met the measurement constraints (west wind, dry). Particle matter was only measured for three days at limited locations. For a broad discussion on the measurement campaign the reader is referred to the ECN report (Weijers *et al.*, 2007). Keeping in mind the results and conclusions of these measurements, recently a second measurement campaign has been started along the A50 close to Zetten, the Netherlands, and a third campaign again in Vaassen is scheduled.

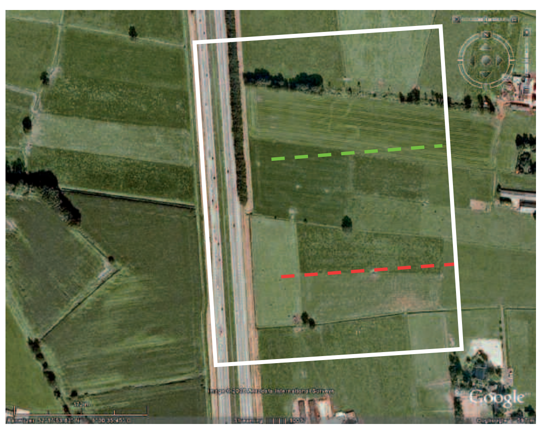

Figure 2. Measurement location Vaassen 2006. The Dashed lines indicate the line along which the measurements were taken (green: with vegetation, red: reference line). The white box indicates the model domain for the simulations. (Source: Google Earth).

4. MODEL COMPARISON

The extended vegetation module in ENVI-met makes the model attractive as a tool to investigate the effects of vegetation on traffic emissions which fits the goals of the IPL project. In a first exercise the model is used to model the five measurement days of the ECN measurement campaign and to make a comparison between model results and measurements. Simultaneously the model results are used to better understand the physics playing a role regarding to the vegetation barrier along the motorway. All results and conclusion will be published by the Dutch Ministry for Transportation soon. In the next sections the model setup and the most important results and conclusions will be briefly presented.

Model setup

The white box in Figure 2 indicates the domain modeled by ENVI-met, this is a total area of 200 by 600 meter and up to 50 meters height. The whole domain is subdivided into non-overlapping elements, 121.688 in total, with a spatial resolution of *6x6x2m* with a vertical refinement in the lowest five cells. Figure 3 shows a detail of the model mesh. The vegetation elements are coloured dark green. The dashed lines and white dots only indicate the position of the ECN measurement positions. They have nothing to do with the model itself.

The traffic emission are modelled as line sources, one line per lane. The emission rates are based on the local traffic counts by the Dutch Ministry of Transportation, multiplied by the Dutch emission factors defined by the Ministry of Housing, Spatial Planning and Environment.

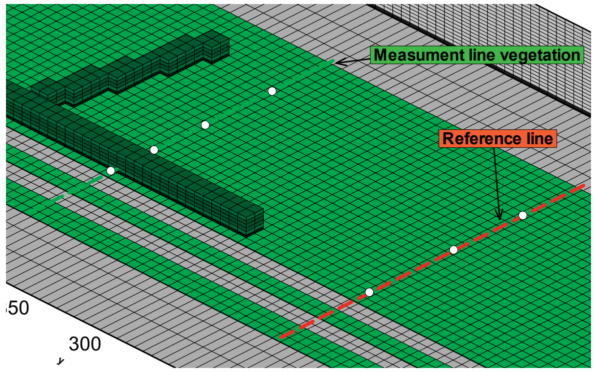

Figure 3. Detail of the model domain, the dashed lines and dots indicate the corresponding position of the ECN measurements.

During the measurement campaign no measurements where taken in the undisturbed area wind upward of the road. Other sources had to be taken to define the meteorological boundary conditions and background concentrations. Meteorological boundary conditions were taken from the HIRLAM model, run by the Dutch Royal Meteorological Institute (KNMI). However, this is a national model with a temporal resolution of 3 hours and a spatial resolution of 11 km, with the lowest computed values at 30 meters height. For this reason modelled wind speeds and directions does not always fully agree the measured values. A similar story is through for the background concentrations, which are taken from three rural background stations located about 30 to 45 km from the measurement field.

Model results

Nevertheless the missing of a reference measurement wind upward of the motorway and the short period of measuring, ENVI-met was capable of representing the measurement campaign quite well.

Figure 4 and Figure show the normalized mean concentration for nitrogen oxides and fine particles at two meters height. These are the mean concentrations averaged over the five measurement days (three measurement days for PM) and normalized with the value of the concentration just in front of the vegetation barrier. The plots show both the modeled concentrations, full lines, and the measured mean values, dots with error bars. The red dots and lines represent the measurements and model results in the reference field, while the green dots and lines represent the measurements and model results in front of and behind the vegetation. The green bar indicates the location of the vegetation barrier and the red blocks at the bottom the location of the traffic emissions.

Notice that the normalized model results and measurements fit best for NO_2. However, for NO_2 the model systematically shows a slight underestimation of the concentrations. At the moment it is not fully clear why and further research is necessary. For *NO* the model predicts a slightly faster decay of the concentrations behind the vegetation. For *PM* the model does not follow the measurements. The measurements even show an increase in the concentrations due to the vegetation while the model shows a pattern similar to those of the nitrogen oxides. Notice that for *PM* only a limited measurement data set was available. For this reason it would be to soon to draw hard conclusions on this and further research remains necessary. From a physical point of view, there is no reason to expect *PM* being that different from gases.

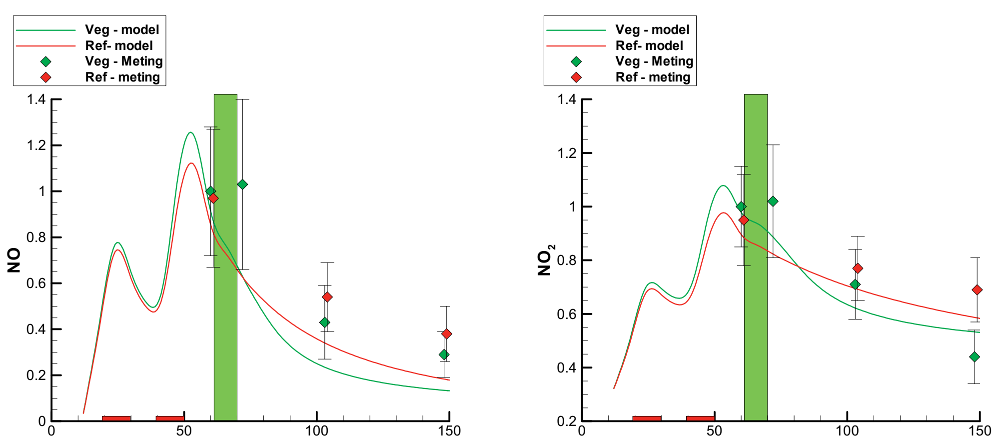

Figure 4. Normalised mean nitrogen oxides concentrations (NO left, NO_2 right) at 2 meters height. Green bar indicates the location of the vegetation, the red boxes the line sources. Green and red dots represent the ECN measurements, continuous lines: model results. Red: Along the reference measurement line, green: in front of and behind the vegetation barrier. Mean wind is blowing from the left.

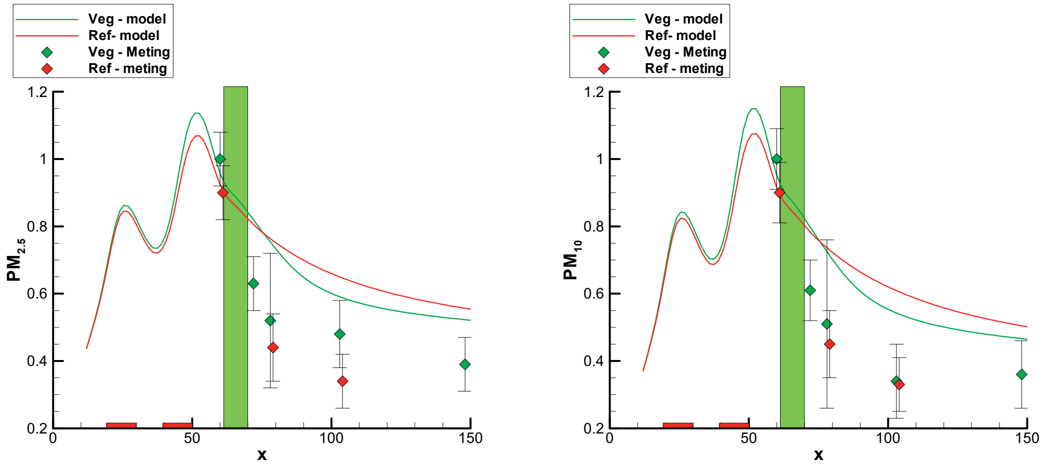

Figure 5. Normalised mean PM concentrations ($PM_{2.5}$ left, PM_{10} right) at 2 meters height. Analogue to Figure 4.

5. EFFECT OF THE VEGETATION ON THE LOCAL AIR QUALITY

In all cases the model predicts an increase in concentration in front of and just behind the vegetation barrier. This is due to the decrease in wind speed at the location of the emission source. Further away from the vegetation a decrease of about 5% and for *NO* even more than 10% can be found. This becomes even more clear if one makes a contour plot of the relative difference between the situation with and without the vegetation barrier as in Figure 6:

$$\Delta C(x,h) = \frac{C(x,y_{ref},h) - C(x,y_{veg},h)}{C(x,y_{ref},h)} \times 100\% \qquad (8)$$

with y_{ref} the location of the reference line and y_{veg} the location of the vegetation line as indicated in Figure 2 and Figure 3. Due to the vegetation a zone with a reduction of more than 10%, locally even up to 30%, is notable. At higher altitudes and in the vicinity of the vegetation the concentrations do increase quite dramatically.

When carefully studying Figure 6, one will notice that the strongest reduction does not appear right behind the vegetation. Earlier ENVI-met results have shown that vegetation can have a negative effect not only in front of the vegetation, but also up to certain meters behind it (Vankerkom *et al.,* 2007). This is confirmed by the measurements as well. This effect is strongly dependent both on the geometry and characteristics of the vegetation, and on the local meteorological conditions as well. Therefore, at this moment it would be rash to just generalise these conclusions. When plotting the differences for NO_2 and *PM* comparable plots appear, but with a reduction of five up to ten percent.

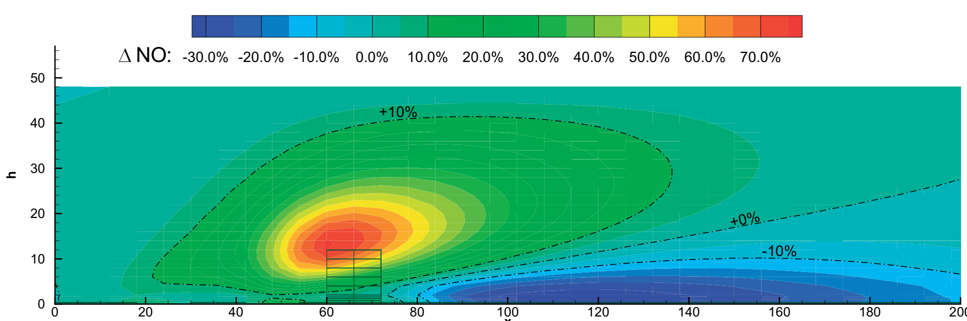

Figure 6. Mean relative difference in NO-concentrations with and without a vegetation barrier.

6. CONCLUSIONS

Both the measurements and the ENVI-met model results show that a vegetation barrier along a motorway can have a local positive effect on the air quality at the downwind side of the motorway. For nitrogen oxides both the model and the measurements show similar relative effects caused by the vegetation. For *PM,* model results do not agree with the measurement campaign. However due to exceptional meteorological conditions, only limited measurement data for *PM* was available. It would be to premature to draw conclusions based on this limited data set.

Both the measurement campaign and the modelling are a first attempt to better understand the effect of a vegetation barrier along a motorway. A second and third big measurement campaign are already started and scheduled in the frame work of the Dutch Air Quality Innovation Programme. Those results will help to give more insight in the processes and to improve the modelling.

REFERENCES

Berkowicz, R. and O. Hertel, 1989: Technical Report DMU LUFT – A131. National Environmental Research Institute, Roskilde, Denmark.

Braden, H., 1982: Simulationsmodell f¨ur denWasser-, Energieund Stoffhaushalt in Pflanzenbest¨anden. *Rep. Inst. Meteorol. Uni. Hannover*, **23**.

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

Bruse, M., 2004: ENVI-met implementation of the Jacobs $A\!-\!g_s$ 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 and Software*, **13**, 373-384.

Liu, J. et al., 1996: E-ε modelling of turbulent air flow downwind of a model forest edge. *Boundary Layer Met.*, **77**, 21–44.

Mellor G. L. and T. Yamada 1975: A simulation of the Wangara atmospheric boundary layer data. *J. Atmos. Sci,*. **32**, 2309–2329.

Samaali, M; Courault, D, Bruse, M.; Olioso, A. and R. Occelli, 2007: Analysis of a 3D boundary layer model at local scale: Validation on soybean surface radiative measurements. *Atmospheric Reseach*, **85**, 183-198.

Schilling, V., 1990: A parameterization for modelling the meteorological effects of tall forests - A case study of a large clearing. *Boundary Layer Met.*, **55**, 283–304.

Seinfeld, J.H. and S.N. Pandis, 2006: Atmospheric chemistry and physics. John Wiley, New Jersey, second edition.

Vankerkom, J., B. De Maerschalck, S. Janssen and F. Tonneijck, 2007: Voorstudie ten behoeve van het uitvoeren van een pilot project langs rijkswegen: Update en gevoeligheidsanalyse van de vegetatiemodule in het ENVI-met model. *Technical report* **DVS-2008-001**, Dutch Ministry of Transport, Public Works and Water Management, Delft, The Netherlands.

Weijers, E. P., G. P. A. Kos, W. C. M. van den Bulk and A. T. Vermeulen, 2007: Onderzoek naar de luchtkwaliteit rondom een vegetatiestrook langs de snelweg. *Technical report* **ECN-E-07-011**, Energy Research Center of the Netherlands.

Wilson, J. D., 1988: A second order closure model for flow through vegetation. *Boundary Layer Met.,* **42**, 371–392.

Yamada, T., 1982: A numerical model study of turbulent airflow in and above a forest canopy. *J. Met. Soc. Japan*, **60**, 439-454.