Flow Through Deciduous Tree Crowns

Comparison of Measurements and High Resolution Numerical Modelling

NATO Advanced Study Institute, May 4 - May 15 2004, Kyiv

Helga Lauerbach\textsuperscript{1} and Joachim Eichhorn\textsuperscript{2}

\textsuperscript{1} Institute of Regional Science, University of Karlsruhe, Germany
\textsuperscript{2} Institute for Atmospheric Physics, University of Mainz, Germany
Overview

- Introduction
- Description of the measuring site
- Results of measurements
- The numerical model MISCAM
  - Basic equations
  - Parameterization of vegetation
- Results of numerical simulations
- Discussion
Introduction

- Project background (measurements)
  - Analysis of the particle (PM$_{10}$) filtering potential of vegetation
  - Deposition as a boundary layer phenomenon (pathways, parameters)
  - Parameterization of flow through vegetation
  - Process understanding
  - Comparison with microscale modelling
Introduction

- Project background (modelling)
  - Effects of different types of vegetation on microscale flow
  - Impacts on pollutant dispersal, esp. deposition
  - Contribution to model evaluation
  - Extension of range of applicability
The measurement site

- Open space in an urban setting
- UCL, irregular flow, even at night
- Next to a busy road
- Single tree (within a row of similar specimens)
The measurement site
Instrumentation

- Wind speed measurements
  - Ultrasonic anemometers
  - Wind vane and cup anemometer
  - Thermal globe anemometers
Measuring setup

- Cross-sectional registration of wind speed at 5.5 m above ground
- Registration of wind speed in the lower part of the crown
- Continuous registration at 13 m above ground
- Vertical wind profile south of the tree (1-6 m)
- Linear extrapolation of the wind speed distribution
Results of measurements

Horizontal wind speed distribution at \( z = 5.5 \) m.
Results of measurements

Vertical wind speed distribution
as seen from S (left) and N (right)
The numerical model MISCAM

- Microscale climate and air pollution model
- Three-dimensional non-hydrostatic flow model
- Explicit modeling of buildings
- Modified $k$-$\varepsilon$ model of turbulence
- Eulerian pollutant dispersal model (optional)
- Parameterization of vegetation following Green (1992)
The numerical model MISCAM

Basic equations - turbulence model

\[ \frac{\partial k}{\partial t} + \frac{\partial u_j k}{\partial x_j} = \frac{\partial}{\partial x_j} \left( c_\mu \frac{k^2}{\varepsilon} \frac{\partial k}{\partial x_j} \right) + P_{m,k} + P_h - \varepsilon \]

(1)

\[ \frac{\partial \varepsilon}{\partial t} + \frac{\partial u_j \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left( c_\mu \frac{k^2}{\sigma} \frac{\partial \varepsilon}{\partial x_j} \right) + c_1 \frac{\varepsilon}{k} (P_{m,\varepsilon} + P_h) - c_2 \frac{\varepsilon^2}{E} \]

(2)
The numerical model MISCAM

Basic equations - production rates

\[
\begin{align*}
P_{m,k} & = 0.5c_{\mu} \frac{k^2}{\varepsilon} \sqrt{\left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \left( \frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i} \right)} \\
P_{m,\varepsilon} & = 0.5c_{\mu} \frac{k^2}{\varepsilon} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \\
P_h & = -1.35c_{\mu} \frac{k^2}{\varepsilon} \frac{g}{\Theta_0} \frac{\partial \Theta}{\partial x_j} \delta_{3j}
\end{align*}
\]
The numerical model MISCAM

Basic equations - flow field

\[
\frac{\partial \tilde{u}_i}{\partial t} = -\frac{\partial u_j u_i}{\partial x_j} + \frac{\partial}{\partial x_j} \left[ c_\mu \frac{k^2}{\varepsilon} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] \tag{6}
\]

\[
\frac{\partial^2 p'}{\partial x_i^2} = -\frac{\rho}{\Delta t} \frac{\partial \tilde{u}_i}{\partial x_i} \tag{7}
\]

\[
u_i = \tilde{u}_i - \frac{\Delta t}{\rho} \frac{\partial p'}{\partial x_i} \tag{8}
\]

\[
\frac{\partial u_i}{\partial x_i} = 0 \tag{9}
\]
The numerical model MISCAM

Parameterization of vegetation

\[
\left( \frac{\partial \tilde{u}_i}{\partial t} \right)_{veg} = \left( \frac{\partial \tilde{u}_i}{\partial t} \right)_{old} - c_d n L v u_i \tag{10}
\]

Drag force dependant on stand density \( n \), leaf area density \( L \), total velocity \( v \) and velocity component under concern.

\( c_d = 0.2n^2 \): empirical drag coefficient
Parameterization of vegetation

\[
\left( \frac{\partial k}{\partial t} \right)_{veg} = \left( \frac{\partial k}{\partial t} \right)_{old} + c_d n L v^3 - 4 c_d n L v k \tag{11}
\]

\[
\left( \frac{\partial \varepsilon}{\partial t} \right)_{veg} = \left( \frac{\partial \varepsilon}{\partial t} \right)_{old} + \frac{3 \varepsilon}{2 k} c_d n L v^3 - 6 c_d n L v \varepsilon \tag{12}
\]

Increased production rates implied by Eq. (10)
Reduction of \( k, \varepsilon \) as proposed by Green (1992)
Results (1)

- Two-dimensional flow through a homogeneous tree stand
- Comparison to wind tunnel data (Green, 1992)
- Results already published (Ries & Eichhorn, 2001)
Comparison to wind tunnel data

Horizontal wind speed (m/s, left) and turbulent kinetic energy (m²/s², right) at $z = 0.25 \, h$ ($h$: height of trees)
Comparison to wind tunnel data

Horizontal wind speed (m/s, left) and turbulent kinetic energy (m²/s², right) at \( z = 0.75 \, h \) (\( h \): height of trees)
Comparison to wind tunnel data

Horizontal wind speed (m/s, left) and turbulent kinetic energy (m²/s², right) at $z = 1.25 \, h$ ($h$: height of trees)
Results (2)

- Flow through a single tree
- Leaf area density ($L$) from measuring site, grid resolution 0.5 m
- Neighboring trees neglected
- Inflow direction 45° (NE)
- Inflow velocity 1 m/s at $z = 13$ m
Flow through a single tree

Normalized wind speed (left) and pressure perturbation (hPa, right)

horizontal cross-section at \( z = 5.25 \text{ m} \)
Flow through a single tree

Turbulent kinetic energy ($m^2/s^2$, left) and turbulent energy dissipation ($m^2/s^3$, right), horizontal cross-section at $z = 5.25$ m
Flow through a single tree

Normalized wind speed (left) and pressure perturbation (hPa, right),
vertical cross-section SW — NE
Flow through a single tree

Turbulent kinetic energy ($m^2/s^2$, left) and turbulent energy dissipation ($m^2/s^3$, right),
vertical cross-section SW — NE
Discussion

- Wind measurements within tree crown yield some interesting results
- Numerical model MISCAM extended to account for vegetation effects
- Numerical simulations reproduce significant speed reduction within crown as well as local acceleration near trunk
- Quantitative agreement unsatisfactory
- Influence of neighboring trees as well as traffic induced turbulence neglected!
Future work

- More measurements required
- Comparison of computed and observed turbulence quantities (in progress)
- Dispersal simulations, including dry deposition on leaf surfaces
- A lot more . . .