12th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes

UNIVERSITY OF KARLSRUHE (GERMANY)

UNIVERSITY OF SALENTO (ITALY)

Evaluation of Numerical Flow and Dispersion Simulations for Street Canyons with avenue-like Tree Planting by Comparison with Wind Tunnel Data

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Outline

- **I**ntroduction

  - flow and dispersion in street canyon

  - influence of trees: wind tunnel and numerical works in literature

- **A**pproach

  - combination of wind tunnel and CFD modeling

- **R**esults

  - experimental and numerical results/comparison

  - discussion and comparison with previous works

- **S**ummary and **C**onclusions

Introduction

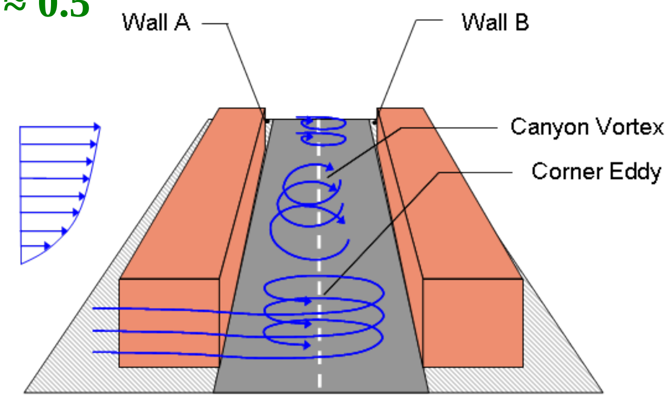
Dispersion in Urban Street Canyons

Street canyon

- **basic unit** forming a city
- where **people and traffic** are
- **geometries** which affect **flow, turbulence fields** and **dispersion**
- where **trees** can be planted

3-D flow field inside a street canyon with aspect ratio H/W ≈ 0.5

- approaching flow perpendicular to street axis
- long street canyons (L/H > 7)
- two dominating vortex structures: **canyon vortex, corner vortex**
- superposition of vortex structures



idealized model of urban street canyon

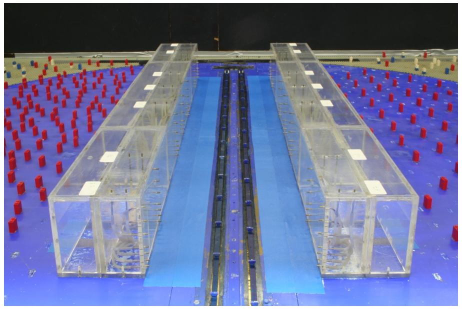
Introduction

Urban Street Canyon and Modeling

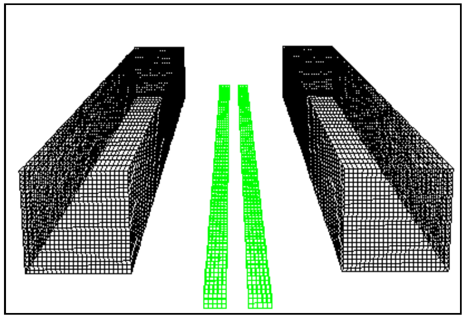
urban street canyon

Idealization

Modeling



street canyon model – wind tunnel

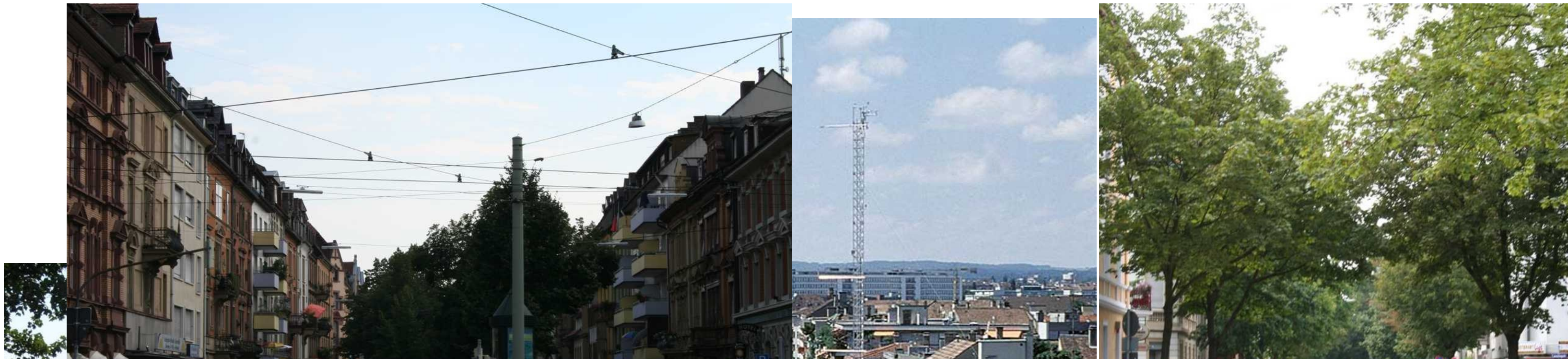


street canyon model– CFD

- idealization of street canyon geometry
- essential geometrical structures
- isolated urban street canyon

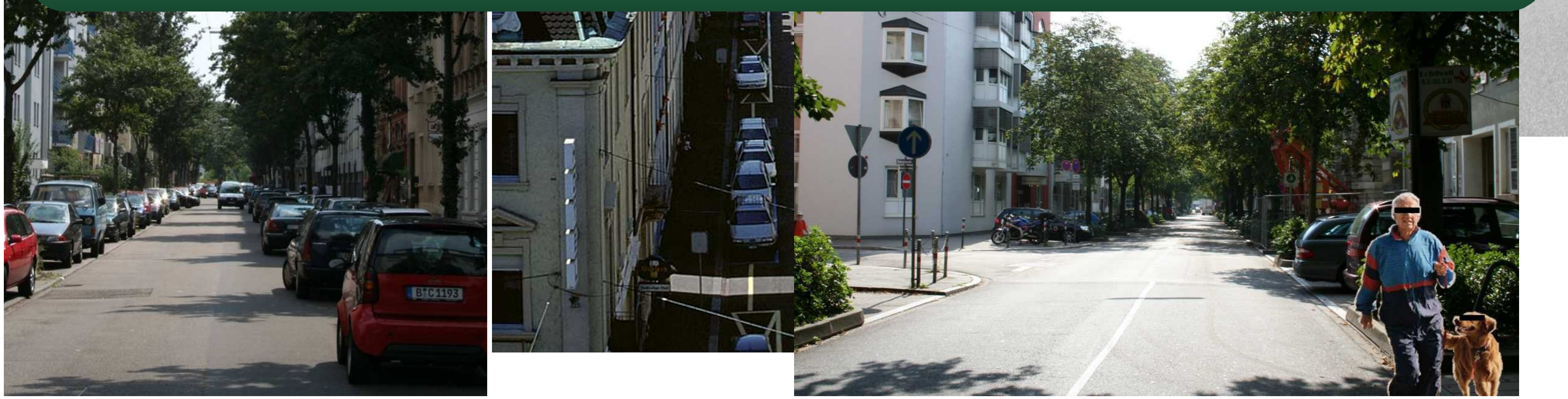
Introduction

Street Canyons with Tree Planting



What is influence of **trees** on

the flow field, natural ventilation and therefore local concentration?



Introduction

Street Canyons with Tree Planting - literature

- **Impact of trees in street canyons on pollutant dispersion not widely considered**
- **Both experimental and numerical investigations are present in literature**

NUMERICAL INVESTIGATIONS

•**Gross G. (1987):**

•influence tree planting (two rows arranged sidewise of the street next to the building walls)

•*k-ε* turbulence closure scheme and modelling of the tree crowns by porous bodies

•decelerated flow velocities near the building walls and increased pollutant concentrations inside the street canyon

•In a similar arrangement**, Ries, K. and J. Eichhorn (2001)** found local increases of the pollution concentration at the leeward wall accompanied by reduced flow velocities due to trees.

2D models applied (do not account for the highly **3D flow fields** present in real urban street canyons of finite length)

Gross, G., 1987: A numerical study of the air flow within and around a single tree. *Boundary Layer Meteorology*, **40**, 311-327.
Ries, K. and J. Eichhorn, 2001: Simulation of effects of vegetation on the dispersion of pollutants in street canyons. *Meteorologische Zeitschrift*, **10**, 229-233.

Introduction

Street Canyons with Tree Planting - literature

WIND TUNNEL INVESTIGATIONS

➢**Gromke, C. and B. Ruck, 2007**: Influence of trees on the dispersion of pollutants in an urban street canyon - Experimental investigation of the flow and concentration field. Atmospheric Environment, 41, 3287-3302

➢**Gromke, C. and B. Ruck**, in press: On the impact of trees on dispersion processes of traffic emissions in street canyons. UAQ2007 Special Issue in Boundary Layer Meteorology, accepted for publication

➢**Gromke, C. and B. Ruck**, 2008: Aerodynamic modeling of trees for small scale wind tunnel studies. Special Issue on Wind and Trees in Forestry, 81, 243 – 258

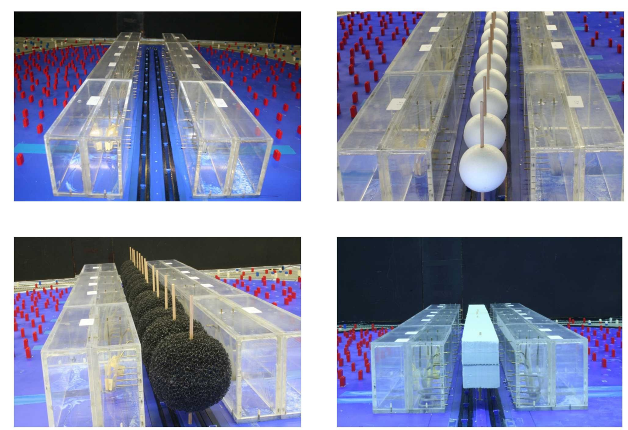
Institute for Hydromechanics - University of Karlsruhe (GERMANY)

Flow and concentration fields in urban street canyons of different aspect ratios with various avenue-like tree planting configurations

Tree planting characteristics**: influence of crown shape, diameter, height, porosity and planting density**

FLOW: **air exchange and entrainment conditions considerably modified**, resulting in lower flow velocities and in overall larger pollutant charges inside the canyon.

DISPERSION: **increases in pollutant concentrations at the leeward and decreases at the windward**



street canyon with miscellaneous tree arrangements

Introduction

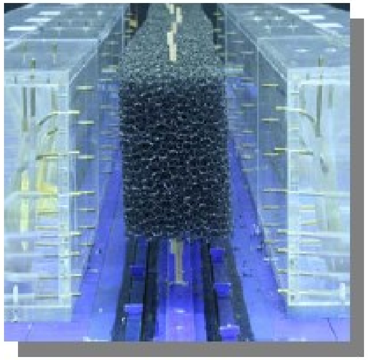
*Street Canyons with Tree Planting – **our previous work***

COMPARISON WT – CFD INVESTIGATIONS (H/W=1)

Empty street canyon

Street canyon with tree planting along the center axis

single block: impermeable



single block: permeable

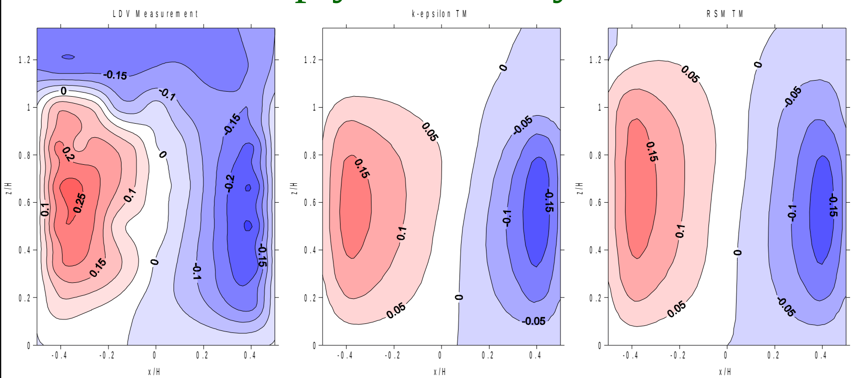
Gromke, C., R. Buccolieri, S. Di Sabatino and B. Ruck, 2008: Dispersion study in a street canyon with tree planting by means of wind tunnel and numerical investigations - Evaluation of CFD data with experimental data. Atmospheric Environment. DOI:10.1016/j.atmosenv.2008.08.019

Introduction

*Street Canyons with Tree Planting – **our previous work***

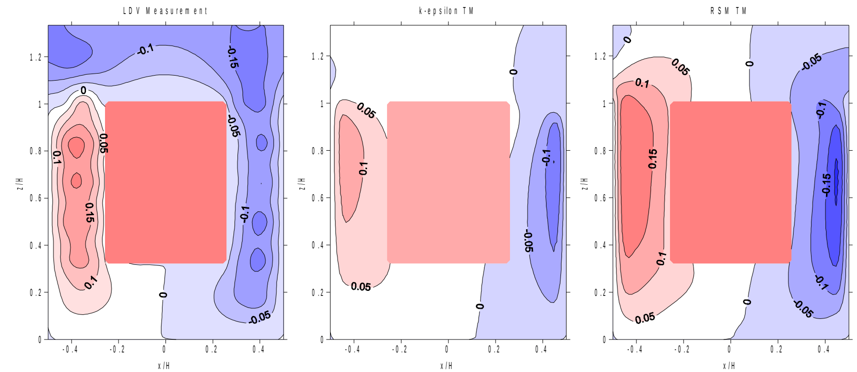
w velocities – middle of the canyon

empty street canyon

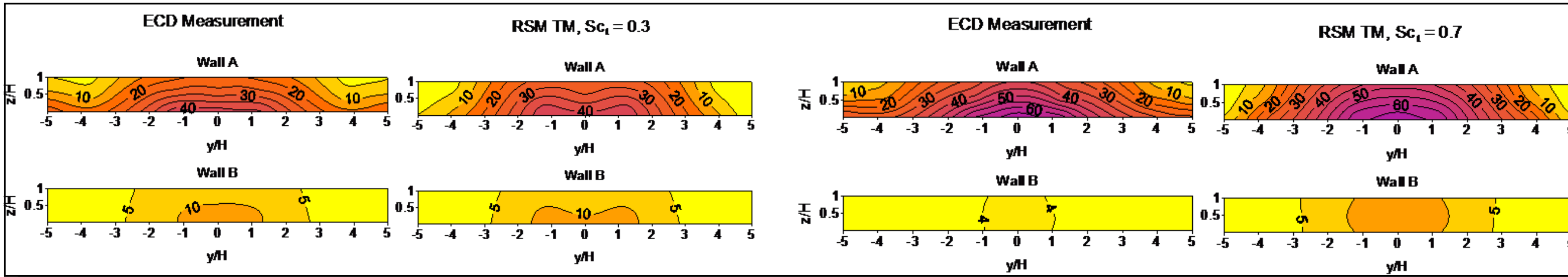


canyon vortex

permeable crown



- **slightly smaller flow velocities in the upward**
- **significantly lower velocities in the downward moving part**
- **volume flow crossing the horizontal plane at *z/H* = 0.7 is reduced (-36 %)**



➢Air volume rotating in **canyon vortex** is reduced in the presence of tree plantings

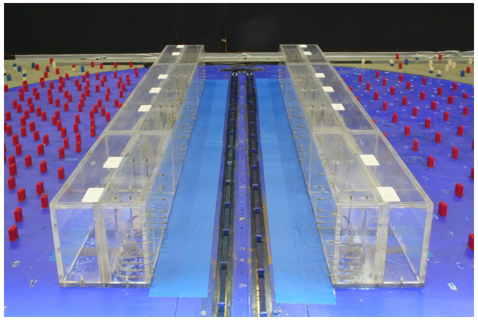
➢**CFD simulations** with FLUENT result in higher pollutant concentrations and lower flow velocities inside the street canyon in comparison with experimental investigations. We need to diminish the Schmidt number

Approach

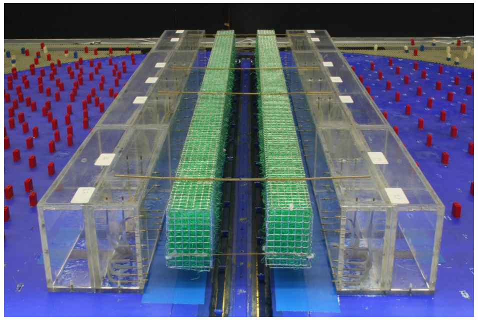
Outline of Investigated Tree Planting Configurations

- Concentration and velocity profiles and contours - Comparison with wind tunnel data
- Approaching flow perpendicular to street axis

Empty street canyon - H/W=0.5



Street canyon with tree planting

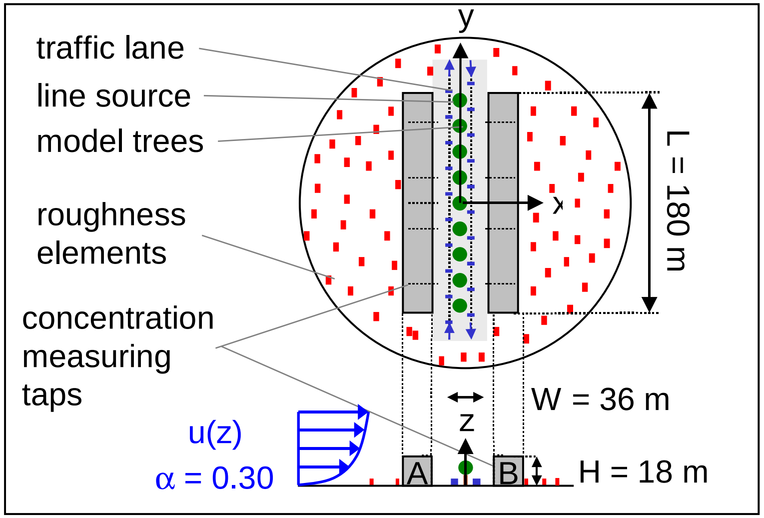


Approach

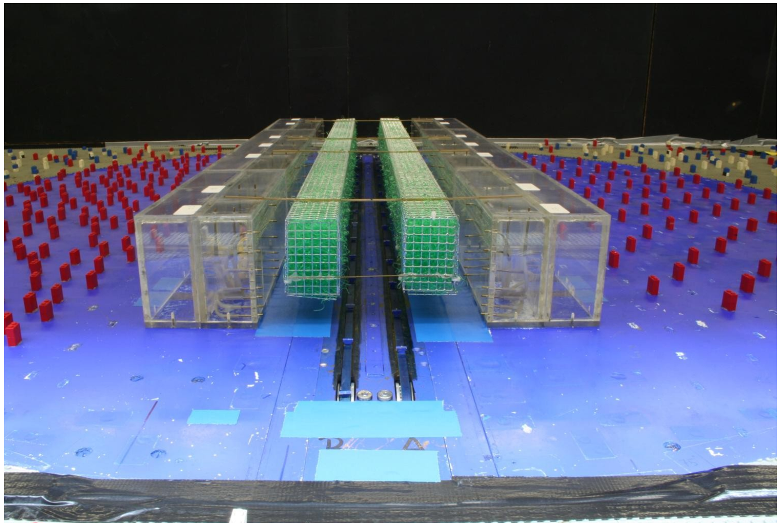
Experimental Investigations in a Boundary Layer Wind Tunnel

Urban street canyon model (scale 1:150)

- *isolated* long street canyon (H/W = 0.5, L/W = 10)
- line source at street level
- tracer gas (sulfur hexafluoride SF_6)
- 126 measurement taps at canyon walls



(Full scale)



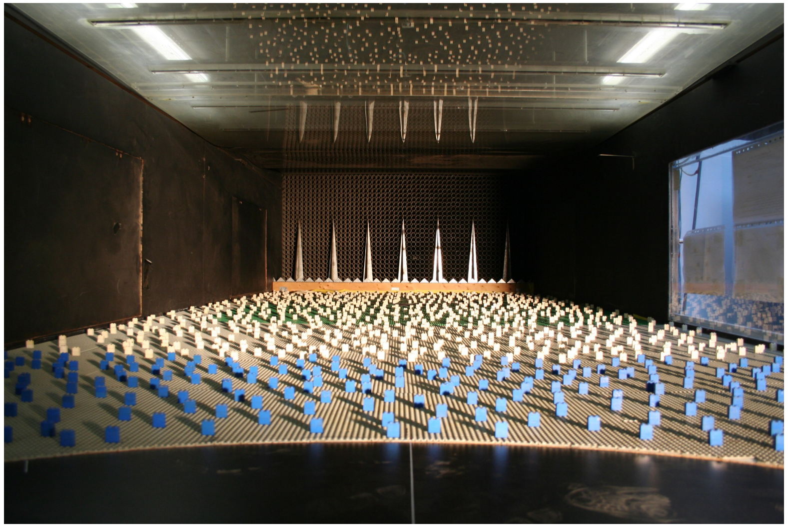
Boundary layer wind tunnel

- closed, circulating BLWT
- vortex generators and roughness elements
- power law profile exponent $\alpha = 0.30$
- u_δ = 7 m/s
- Reynolds-No. Re = 37.000

Approach
Measurement Instrumentation

Concentration Measurements

- **Electron Capture Detector** (ECD) - model Meltron LH 108
- measurement of **mean tracer gas concentrations** (sulfur hexafluoride SF_6)
- **averaging time** for one concentration measurement: about 120 sec
- 14 taps measured simultaneously
- **3 to 4 hours** for each configuration, including the gas analysis



$$c^+ = \frac{c_m \; u_{ref} \; H}{Q_T / l}$$

Dimensionless concentrations c+

c_m	measured concentration
u_{ref}	reference velocity
H	building height
Q_T/l	strength of line source

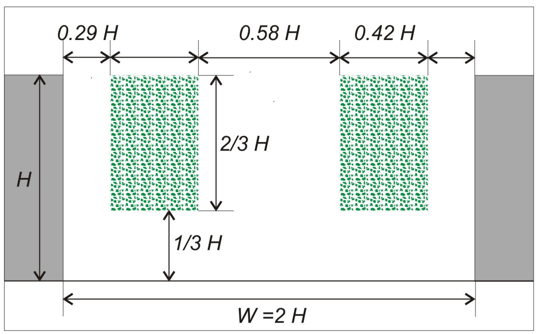
Approach

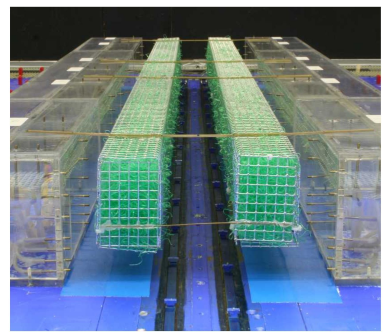
Outline of Investigated Tree Planting Configurations

WT modelling of porous tree crowns

- **custom-made lattice cages** aligned symmetrically along the street axis

- cages divided into 31 cells, filled with **filament/fibre-like synthetic wadding material**





- **pressure loss coefficient** determined in forced convection conditions (to describe the aerodynamic characteristics)

$$\lambda = \frac{\Delta p_{stat}}{p_{dyn}\, d} = \frac{p_{windward} - p_{leeward}}{(1/2)\ \rho u^2 d}$$

Δp_{stat}: difference in static pressure windward and leeward of the porous obstacle
p_{dyn}: dynamic pressure, u: mean wind velocity
d: porous obstacle thickness in streamwise length

- two crown porosities (typical for crown porosities of deciduous trees):
  - **Pore volume fractions of P_{Vol} = 97.5 % (**λ = 80 m^{-1}, **LOOSELY FILLED)**
  - **P_{Vol} = 96 % (**λ = 200 m^{-1}, **DENSELY FILLED)**

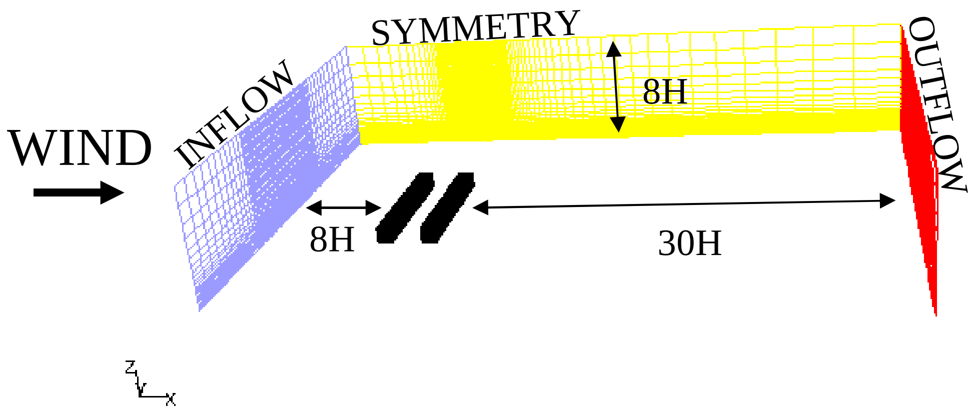
Approach

Numerical Investigations - CFD Simulations with FLUENT

Description of FLUENT simulation setup

- commercial CFD-Code
- RANS-Equations
- turbulence closure schemes
    - RSM
- second order discretization schemes
- grid: hexahedral elements
    - ~ 400,000
    - δ_x=0.05H, δ_y=0.25H, δ_z=0.05H
- turbulent Schmidt number Sc_t = 0.7

$$Sc_t = \frac{\nu_t}{D_t} \quad \left(\frac{\text{turbulent viscosity}}{\text{turbulent diffusivity}} \right)$$



INLET

$$\frac{u(z)}{u_H} = \left(\frac{z}{H} \right)^{\alpha} \quad k = \frac{u_*^{\,2}}{\sqrt{C_\mu}} (1 - \frac{z}{\delta}) \quad \varepsilon = \frac{u_*^{\,3}}{\kappa z} (1 - \frac{z}{\delta})$$

u_H*=4.76 m/s*: undisturbed wind speed at the building height H

α*=0.30*: power law exponent

u=0.52 m/s*: friction velocity

κ*=0.40:* von Kàrmàn constant

C_μ = 0.09

Approach

Outline of Investigated Tree Planting Configurations

CFD modelling of porous tree crowns

- A **cell zone is defined** in which the porous media model is applied and the pressure loss in the flow is determined

- The porous media model adds **a momentum sink in the governing momentum equations**:

$$S_i = -\left(\sum_{j=1}^{3} D_{ij}\mu v_j + \sum_{j=1}^{3} C_{ij}\frac{1}{2}\rho|v|v_j\right)$$

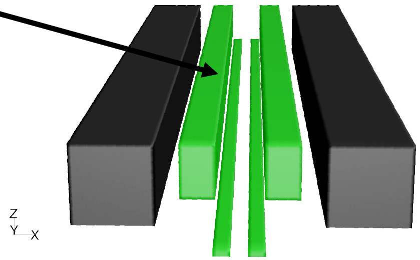
viscous loss term + inertial loss term

Si: source term for the i-th (x, y, or z) momentum equation
$|v|$: magnitude of the velocity
D and C: prescribed matrices

- This momentum sink contributes to the pressure gradient in the porous cell, creating a **pressure drop** that is proportional to the fluid velocity (or velocity squared) in the cell.

- The **standard conservation equations for turbulence quantities** is **solved in the porous medium**. Turbulence in the medium is treated **as though the solid medium has no effect on the turbulence generation or dissipation rates**.

permeable zone with the same loss coefficient λ as in wind tunnel experiments

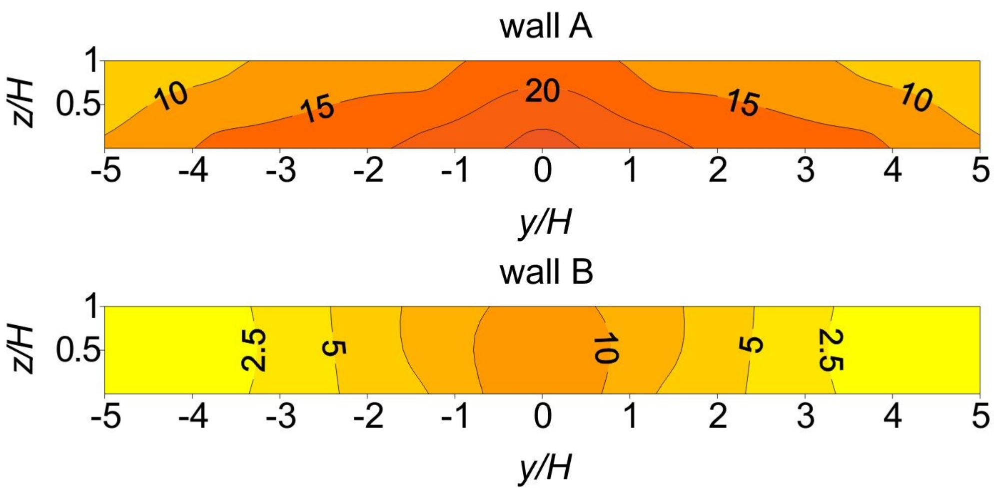


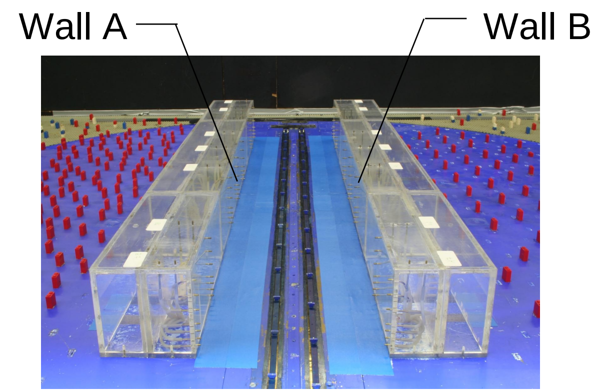
LOOSELY FILLED: λ = 80 m^{-1}

DENSELY FILLED: λ = 200 m^{-1}

Results
Empty Street Canyon

WT CONCENTRATIONS





- **Largest concentrations at the pedestrian level in proximity of wall A**
- **Wall A shows larger concentrations than windward wall B (about 3 times larger)**
- **Decreasing concentrations towards the street ends**

Results

Empty Street Canyon

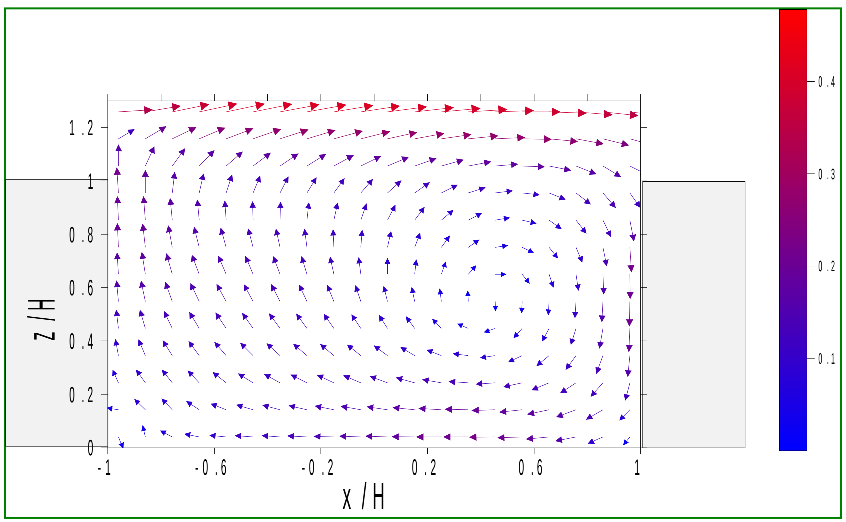
CFD FLOW

➢**Wall A shows larger concentrations than windward wall B:** *dominating vortex-like structure around the street canyon centre*

➢**Decreasing concentrations towards the street ends:** *enhanced natural ventilation at the street canyon ends, where air exchange is not only provided by vertical exchange with the above roof flow but also with entering flow laterally*

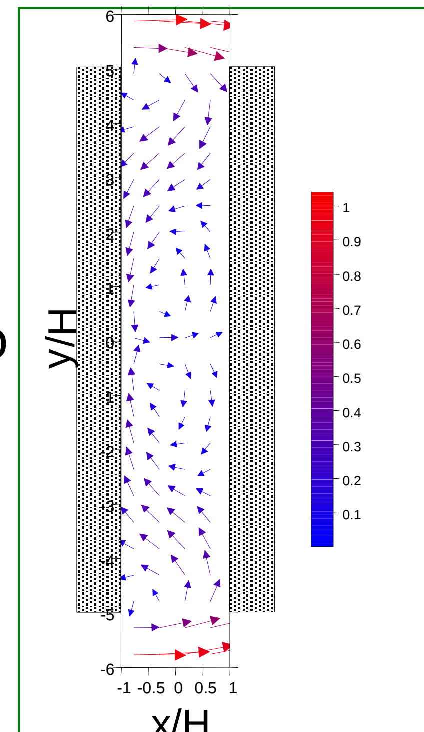
y=1.25H

WIND



z=0.5H

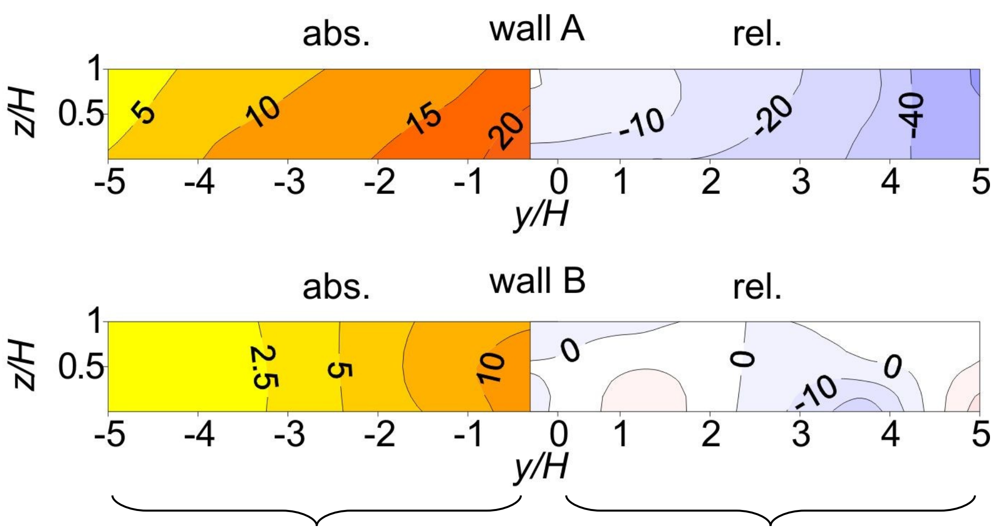
WIND



Results

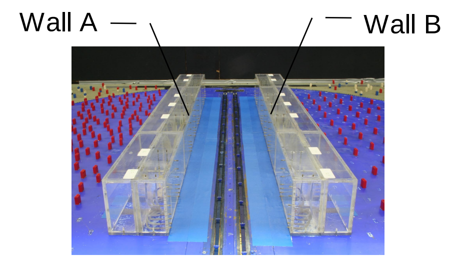
Empty Street Canyon

CFD - WT CONCENTRATIONS

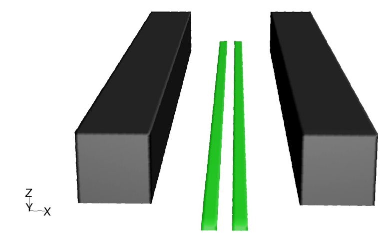


calculated concentrations

relative deviations [%] in respect of measurements



street canyon model – wind tunnel



street canyon model – CFD

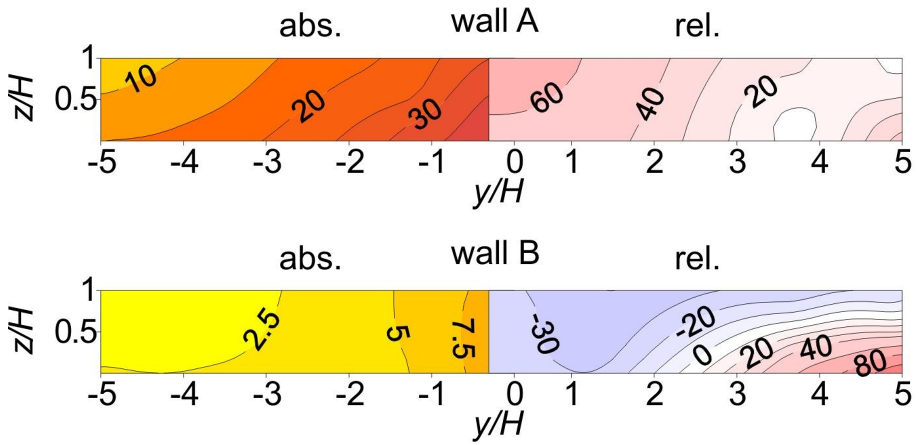
- CFD concentration pattern qualitatively similar to that obtained in the wind tunnel
- Slight underestimation of the measured concentrations in proximity of wall A

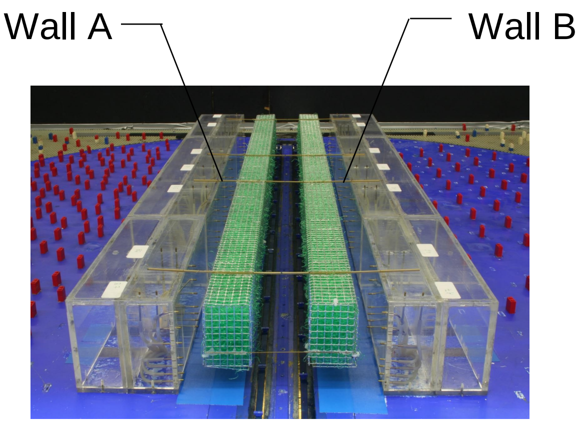
Results

Street Canyon with Tree Planting

Loosely filled Crown

WT CONCENTRATIONS





relative deviations [%] in respect of tree-less street canyon

- **Increases in concentrations in proximity of wall A and decreases near wall B**
- **Maximum concentrations at pedestrian level in proximity of wall A**
- **Differently to the tree-free street canyon case, less direct transport of pollutants from wall A to wall B occurs**

Results

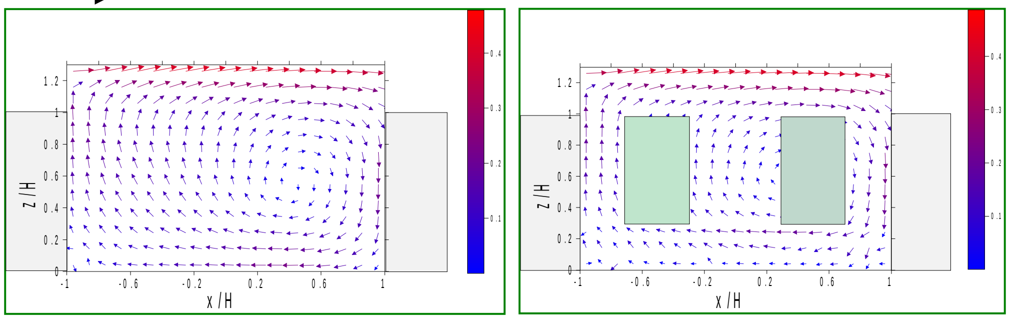
Street Canyon with Tree Planting

Loosely filled Crown

CFD FLOW

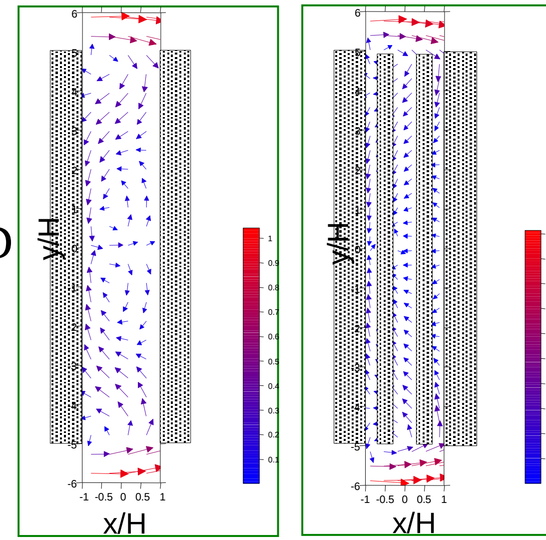
WIND

y=1.25H



z=0.5H

WIND



- **Increases in concentrations in proximity of wall A and decreases near wall B**

The pollutants are advected towards the leeward wall A, but, since the circulating fluid mass is reduced in the presence of tree planting, the concentration in the uprising part of the canyon vortex in front of wall A is larger

- **Differently to the tree-free street canyon case, less direct transport of pollutants from wall A to wall B occurs**

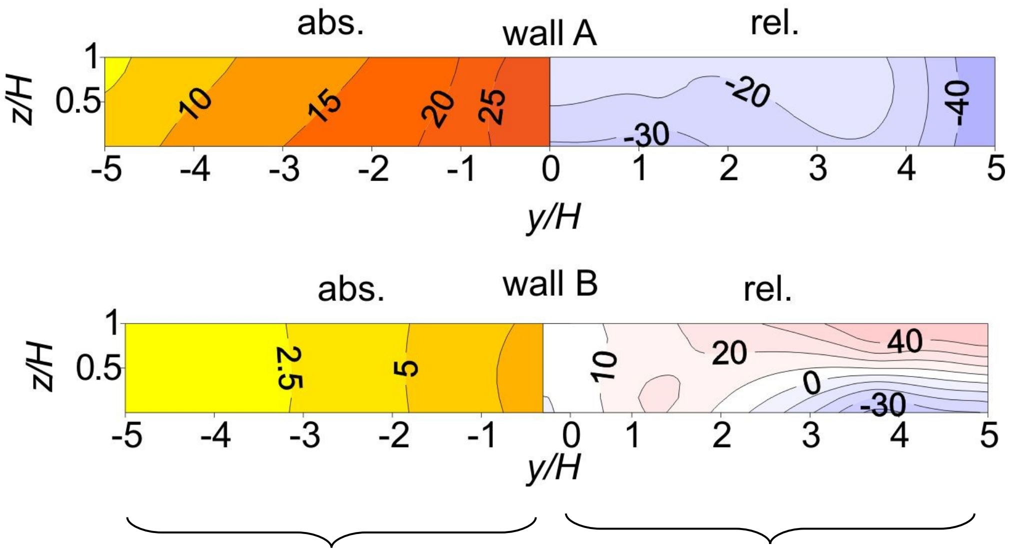
Most of the uprising canyon vortex is intruded into the flow above the roof level. Here, it is diluted before partially re-entrained into the canyon. As a consequence, lower traffic exhaust concentrations are present in proximity of wall B

Results

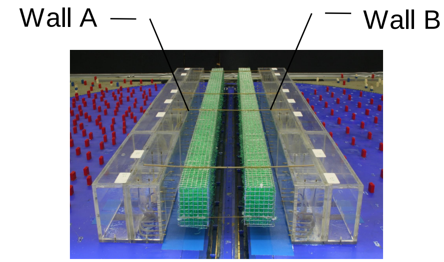
Street Canyon with Tree Planting

Loosely filled Crown

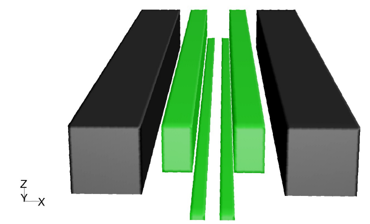
CFD - WT CONCENTRATIONS



calculated concentrations **relative deviations [%] in respect of measurements**



street canyon model – wind tunnel



street canyon model – CFD

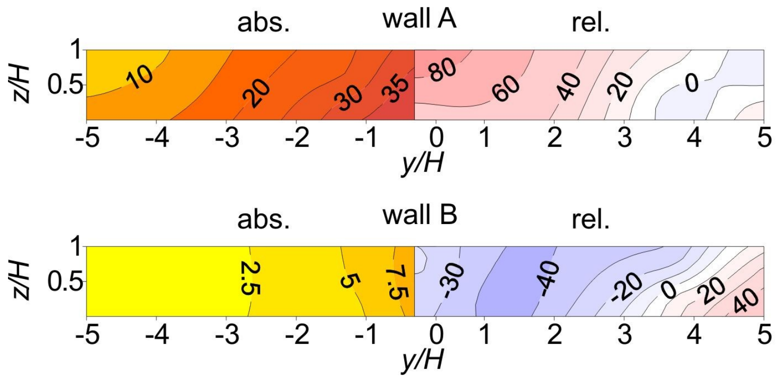
- **FLUENT is successful in predicting an increase in concentrations in proximity of wall A and a decrease near wall B and the relative deviations in respect of tree-less street canyon**
- **As in the tree-free case, it slightly underestimated experimental data**

Densely filled Crown

Results

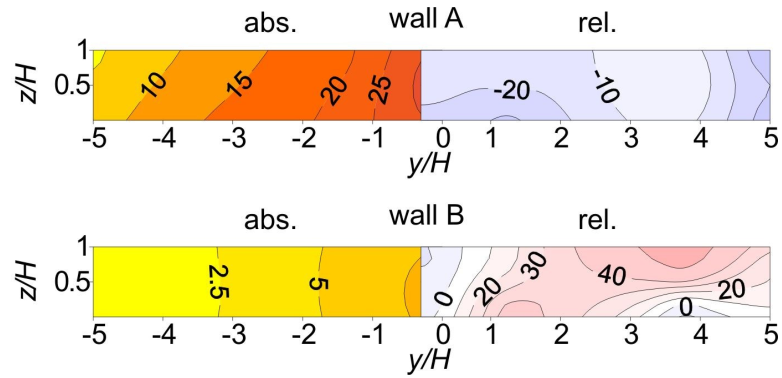
Street Canyon with Tree Planting

WT CONCENTRATIONS



relative deviations [%] in respect of tree-less street canyon

CFD - WT CONCENTRATIONS



calculated concentrations

relative deviations [%] in respect of measurements

➢**In comparison to the street canyon with the tree planting of loosely filled crown, no essential changes are found both in wind tunnel experiments and CFD simulations**

The degree of crown porosity is of minor relevance for flow and dispersion processes inside the street canyon as the tree planting is arranged in a sheltered position with wind speeds being very small.

Results

Discussion and Statistical analysis

Statistical analysis (Chang, C. and S. Hanna, 2004):

- normalized mean square error (NMSE ≤ 4)
- correlation coefficient (R)
- fraction of predictions within a factor of two of observations (FAC2 ≥ 0.5)
- fractional bias (−0.3 ≤ FB ≤ 0.3)

	NMSE	R	FAC2	FB
tree-less street canyon	0.06	0.96	0.97	0.15
large crown porosity (P_{Vol} = 97.5 %)	0.13	0.98	1.00	0.21
small crown porosity (P_{Vol} = 96 %)	0.09	0.99	1.00	0.14

Comparison Wind Tunnel Measurements - Numerical Computations

- CFD simulations are in **general good agreement** with wind tunnel experiments
- Pollutant concentrations in proximity of the leeward wall are slightly underestimated in the numerical simulations, while near the windward wall both slightly over- and underestimations are present

Summary and Conclusions

- The **combination of experimental and numerical investigations** in a novel aspect of research can provide a **strategy to investigate pollutant dispersion in street canyons with tree planting**, to obtain useful suggestions for assessment, planning and implementation of exposure mitigation in urban areas.

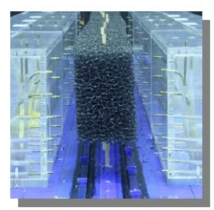
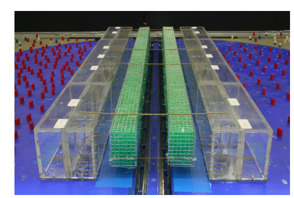
Influence of Trees on Flow Field and Pollutant Dispersion in Street Canyons

- **In-canyon air quality** can be significantly **altered by avenue-like tree planting**
- Air volume rotating in **canyon vortex is reduced** by the presence of tree plantings
- Avenue-like tree planting cause **overall increase** in concentrations
- **Increases** in concentrations at the **leeward wall** and **decreases** at the **windward wall**

Summary and Conclusions

➢Concentration fields within street canyon depend on both street canyon aspect ratio and tree planting configuration

➢Double tree rows is preferable to one row in the middle of the canyon

Relative deviation in concentration	**H/W=1 –single tree row vs empty** 	**H/W=0.5 –two tree rows vs empty** 
leeward	+71%	+42%
windward	-35%	-32%

CODASC Database
by Christof Gromke

- ➢**Database containing concentration measurement data of street canyons with tree planting**
- ➢It is meant **for modelers** (so all the necessary boundary conditions, like wind tunnel profile, geometry, etc.... are provided)

CODASC Database
by Christof Gromke

- ➢Data from **40 experiments on street canyon/tree planting configurations**
- ➢**Free for download**
- ➢**Online next month** at:

http://www.ifh.uni-karlsruhe.de/science/aerodyn/CODASC.htm

THANK YOU FOR YOUR ATTENTION!