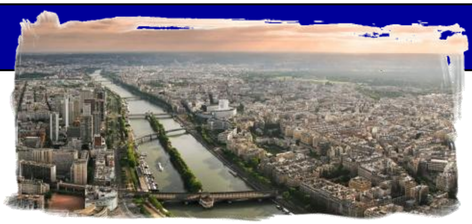
Study of tree-atmosphere interaction and assessment of air quality in real city neighbourhoods



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HARMO13

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UNIVERSITY OF VENICE (ITALY)

UNIVERSITY OF SALENTO (ITALY)

STUDY OF TREE-ATMOSPHERE INTERACTION AND ASSESSMENT OF AIR QUALITY IN REAL CITY NEIGHBOURHOODS

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Outline

- **I**ntroduction
  - Background ideas / urban areas (buildings, trees ..)
- **C**FD **s**imulations / validation
  - Aerodynamic effects of trees in street canyons (IDEALISED)
  - Application to a real case scenario - Bari city (Italy)
- **C**onclusions and future perspective

Introduction

Urban street canyons

STREET CANYON

- city basic geometry unit
- geometries which affect flow and turbulence fields
- ***aspect ratio***, W/H

Street canyon

- ➢where the **people and (the emissions)** are
- ➢where **trees** can be planted
- ➢direct **CFD**/LES is practicable
- ➢**operational modeling** is typically based on a more idealized recalculating vortex driven by a shear layer
- ➢**traffic pollutants** released near the ground need to be "effectively" dispersed to maintain "adequate" **air quality**

Introduction

Example of Urban street canyons

Street canyon without trees

Street canyon with one-row trees

Street canyon with two-rows trees

Where are we?

- Impact of trees in urban areas on pollutant dispersion **not widely considered**
- Both **experimental and numerical investigations** are present in the literature
- Some of the tree effects on flow and dispersion have been considered individually in previous works, such as **deposition, filtration, blockage** etc.
- Still **far from a comprehensive understanding of the overall role** plaid by vegetation on urban air quality

- **One of the most extensive review is given by Litschke and Kuttler (2008),** who reported on several field studies as well as numerical and physical modelling of filtration performance of plants with respect to atmospheric dust.

particle deposition on plant surfaces → **pollutant concentration reduced**

obstacles to airflow (air mass exchange reduced) → **pollutant concentration increased**

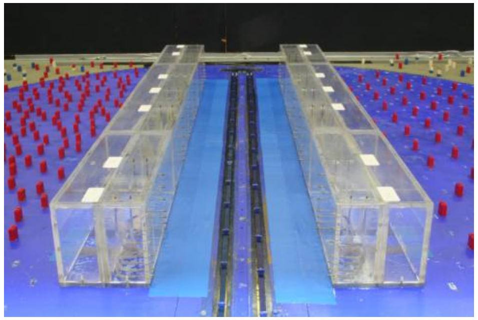
Litschke, T and Kuttler, W., 2008. On the reduction of urban particle concentration by vegetation – a review. Meteorologische Zeitschrift 17, 229-240.

CFD modelling

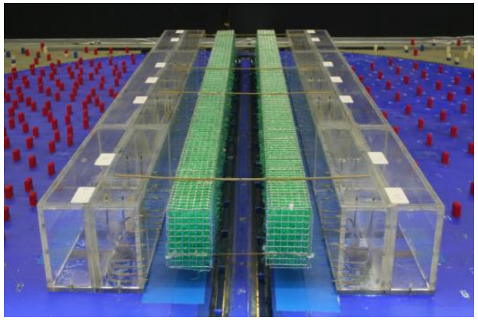
Validation studies (W/H=2)

1) Approaching flow **perpendicular and inclined by 45°** to street axis

- **Empty street canyon - W/H=2**



- **Street canyon with tree planting**



2) Is **wind direction** important? Competition with **aspect ratio**…

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CFD modelling

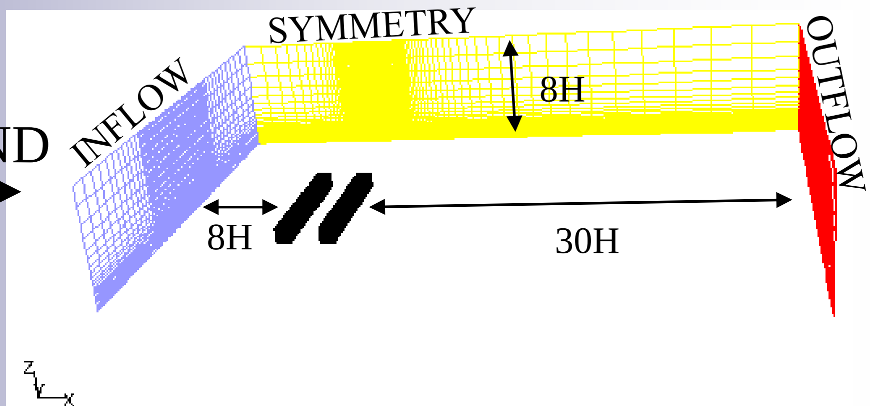
Objectives: Validation studies / speculative approach

Example of a typical CFD simulation setup

- commercial CFD-Code
- RANS-Equations
- turbulence closure schemes
  - RSM **at least!**
- second order discretization schemes
- grid: hexahedral elements
  - ~ 400,000 – 1,000,000
  - δ_x=0.05H, δ_y=0.25H, δ_z=0.05H
  - expansion rate <1.3
- turbulent Schmidt number Sc_t = 0.7

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

WIND



INLET

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

u_H=*4.7 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

Dimensionless concentrations c+

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

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

CFD modelling

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**:

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

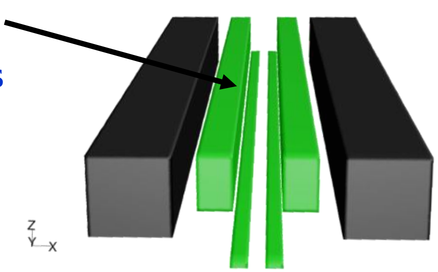
viscous loss term + inertial loss term

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}

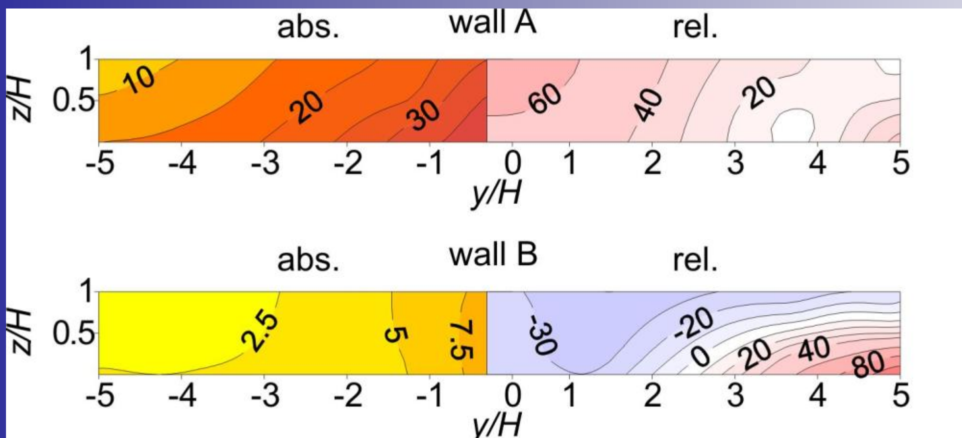
STREET CANYON WITH TREES

CFD modelling

Validation studies (W/H=2)

wind direction: perpendicular

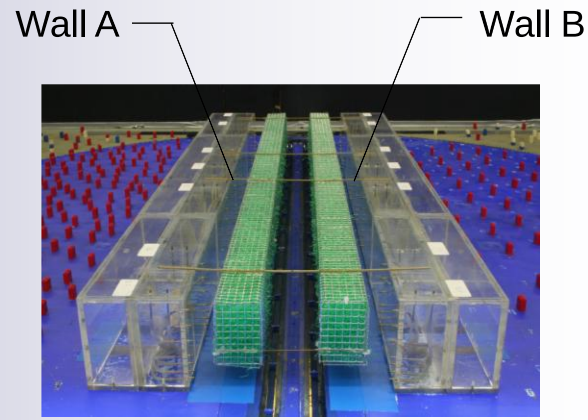
WT CONCENTRATIONS



Measured concentrations | **Relative deviations [%] in respect of tree-free street canyon**

Loosely filled crown

(λ = **80 m^{-1}**, P_{Vol} = 97.5 %)



- ➢**Concentration increase in proximity of wall A and decrease 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**

STREET CANYON WITH TREES

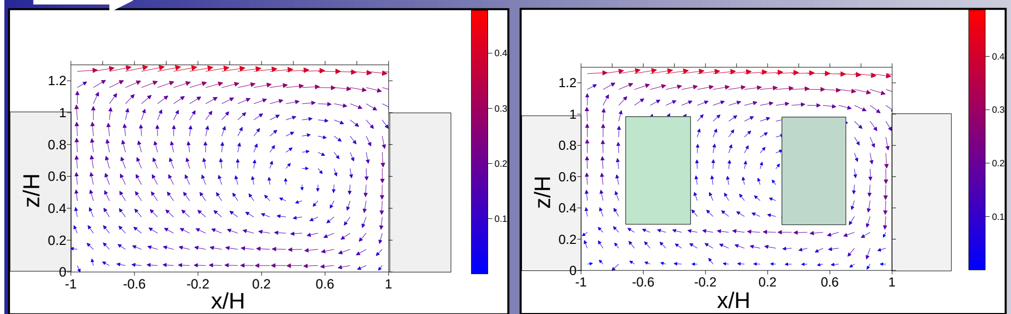
CFD modelling

Validation studies (W/H=2)

wind direction: perpendicular

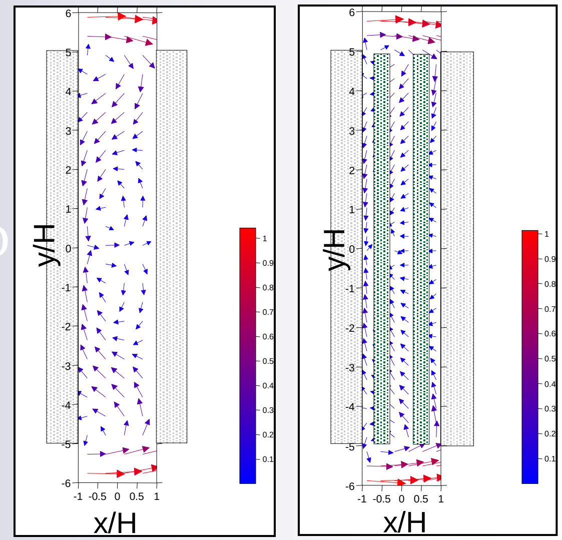
WIND

y=1.25H



WIND

z=0.5H



- **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

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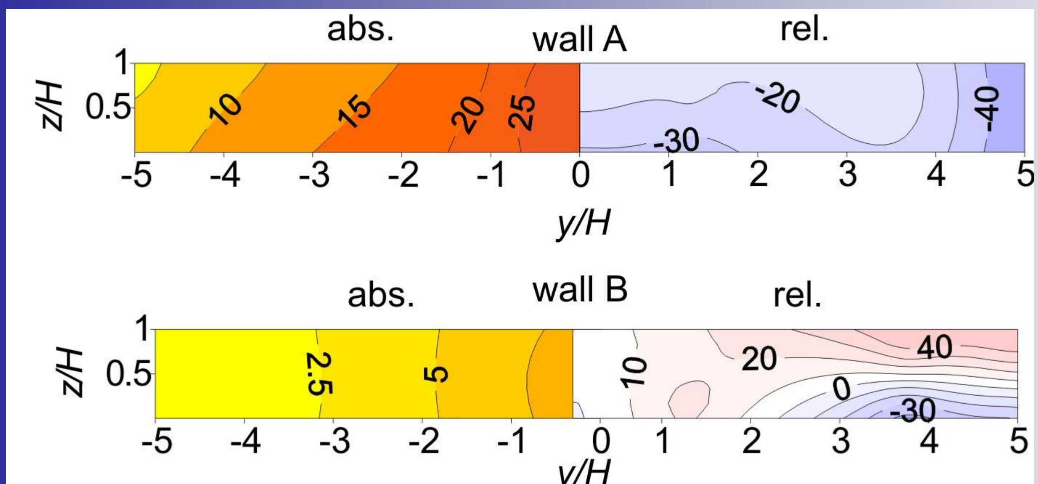
STREET CANYON WITH TREES

CFD modelling

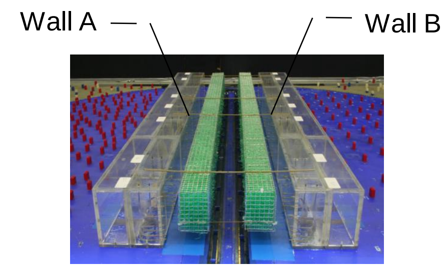
Validation studies (W/H=2)

wind direction: perpendicular

CFD - WT CONCENTRATIONS



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



street canyon model – wind tunnel

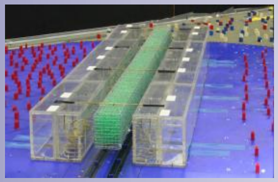
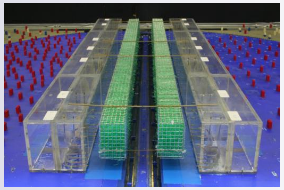
street canyon model – CFD

- **CFD simulations were 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-free street canyon**
- **As in the tree-free case, it slightly underestimated experimental data**

Sensitivity to the aspect ratio

wind direction: perpendicular

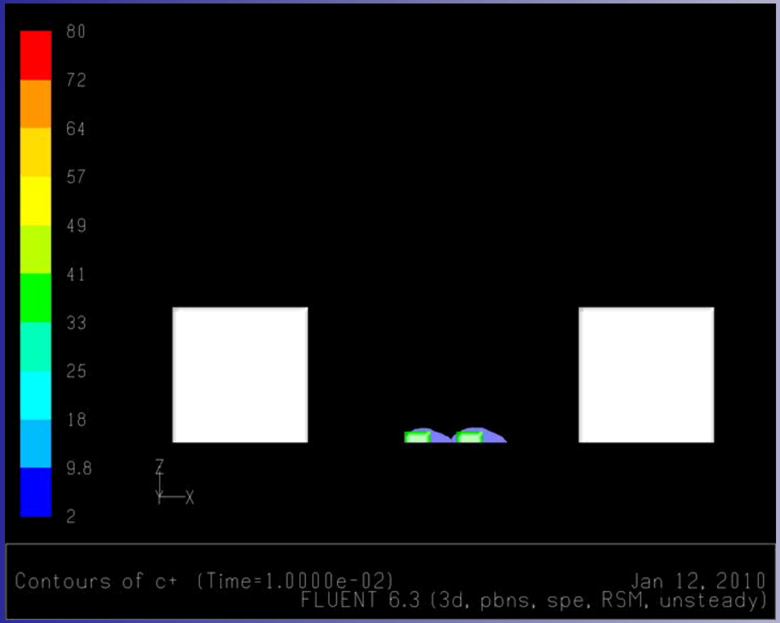
- Concentration fields within street canyon depend on both street canyon aspect ratio
- **The degree of crown porosity is of minor relevance** for flow and dispersion processes inside the street canyon as the tree planting is arranged in a sheltered position with wind speeds being very small.
- **Double tree rows is preferable to one row in the middle of the canyon**

Relative deviation in wind tunnel concentration	W/H=1 –single tree row vs empty 	W/H=2 –two tree rows vs empty 
leeward	+71%	+42%
windward	-35%	-32%

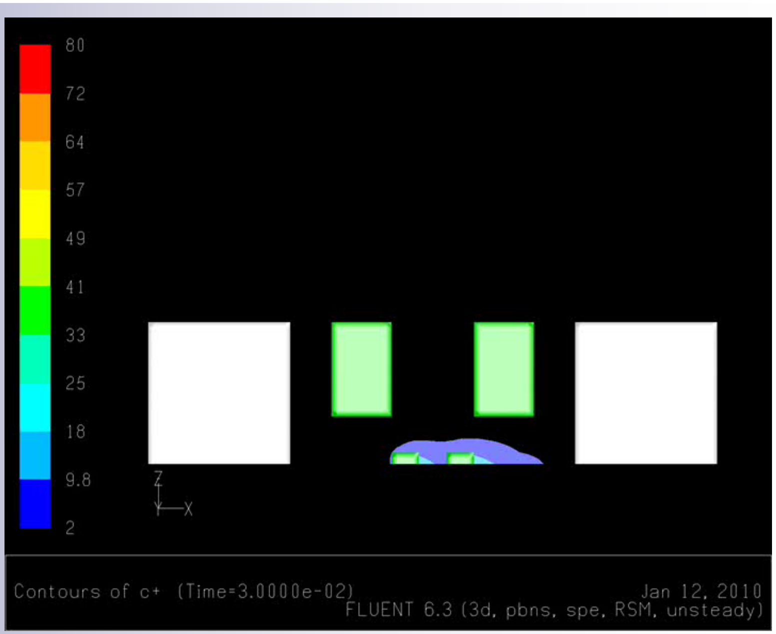
CFD modelling

Flow and dispersion in street canyons with tree planting

Tree-free street canyon



Street canyon with tree planting (densely filled crown)



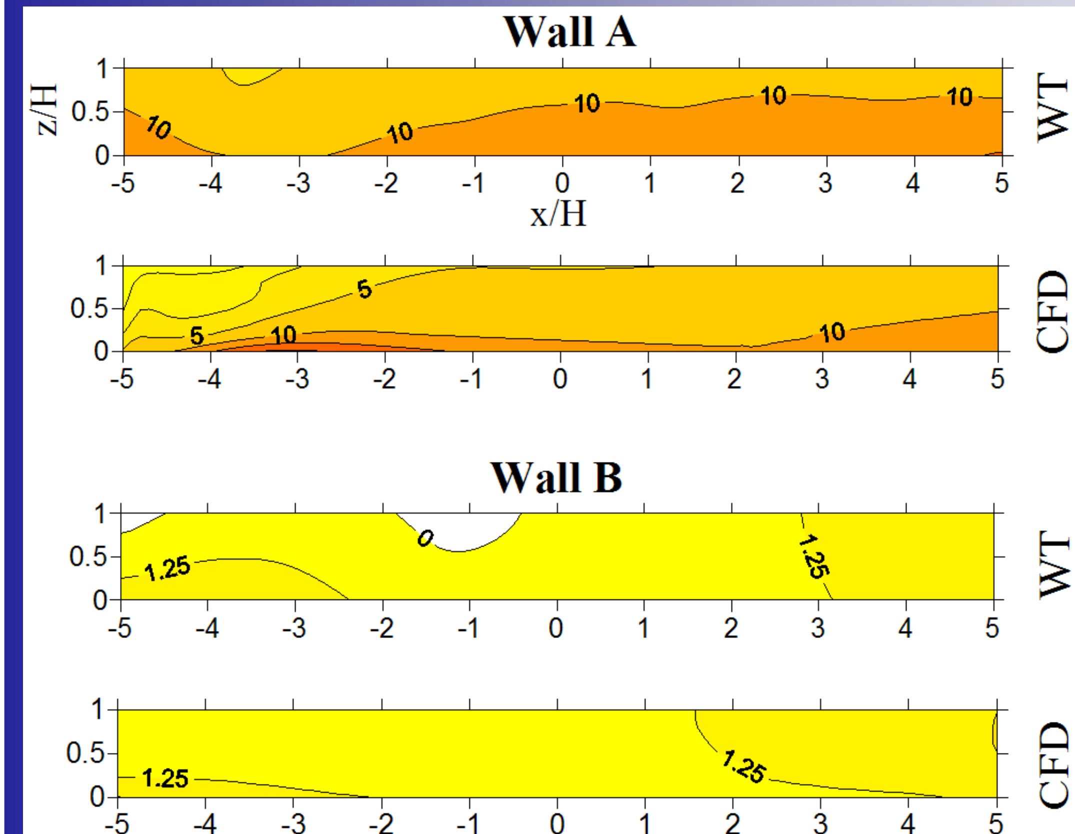
EMPTY STREET CANYON

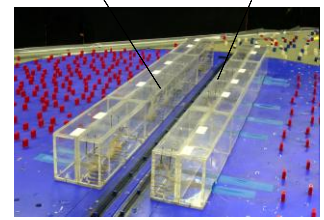
CFD modelling

Validation studies (W/H=2)

wind direction: 45°

CFD - WT CONCENTRATIONS





street canyon model – wind tunnel

- Pollutant concentrations are larger than at wall B. Concentration increases from the centre to the street ends at both walls are found.
- In the wind tunnel experiments, at the beginning of wall A large concentrations are found. This phenomenon is only partially reproduced in the CFD simulations.
- Overall CFD concentrations are similar to those obtained in the wind tunnel, even if there is some underestimation of the measured concentrations at wall A.

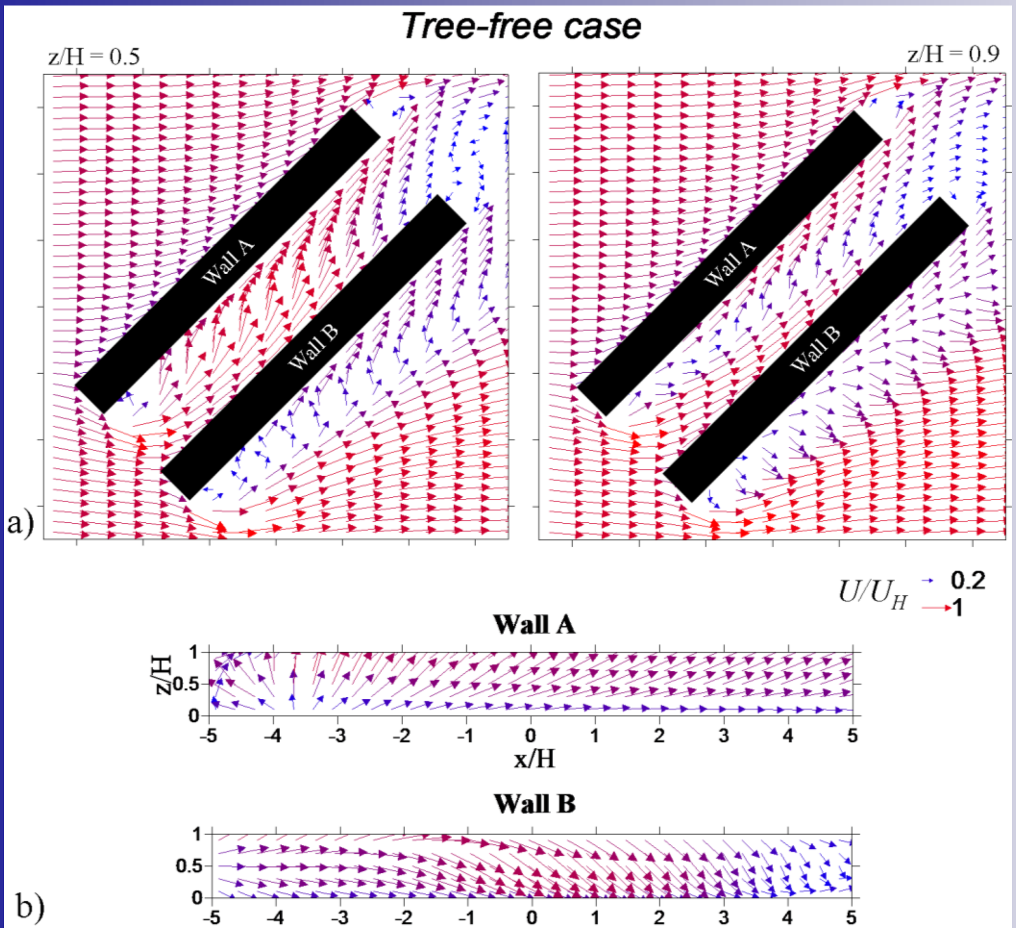
CFD modelling

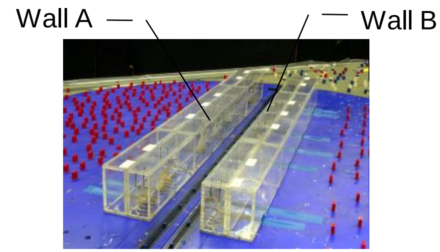
Validation studies (W/H=2)

EMPTY STREET CANYON

wind direction: 45°

CFD FLOW





street canyon model – wind tunnel

- ➢Lower concentrations at both walls at the upstream entry are due to enhanced ventilation caused by the superposition of the canyon vortex and the corner eddy.

- ➢The increasing pollutant concentrations towards the downstream end of the street clearly indicate that the flow along the street axis becomes a dominant pollutant transport mechanism.

- ➢This tendency is due to the helical flow characteristic of the canyon vortex. Moreover, the clockwise rotating helical motion determine the vertical concentration distributions on both walls.

EMPTY STREET CANYON

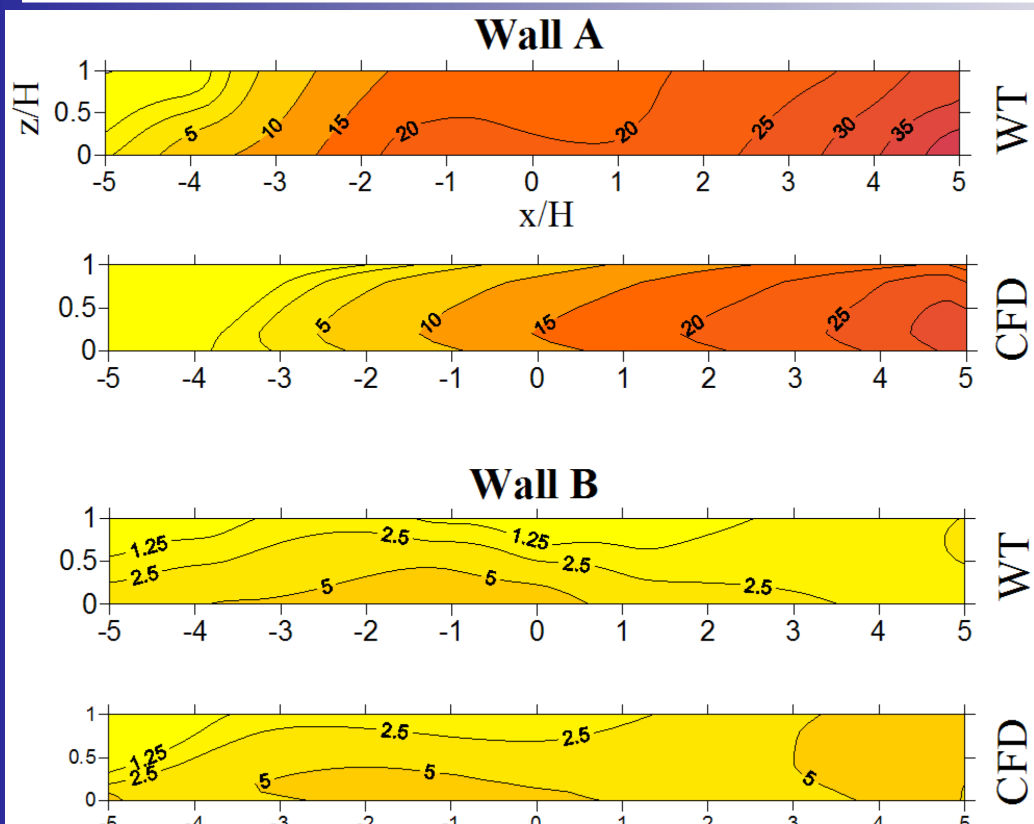
CFD modelling

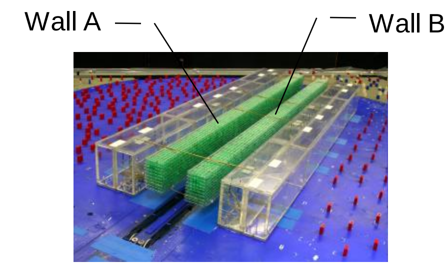
Validation studies (W/H=2)

wind direction: 45°

Densely filled crown (λ = 200 m^{-1} , P_{Vol} = 96 %)

CFD - WT CONCENTRATIONS





street canyon model – wind tunnel

➢**Increases in concentrations at both walls**.

➢Overall CFD concentrations are similar to those obtained in the wind tunnel, even if there is an underestimation of the measured concentrations at wall A, especially close to the upstream entry.

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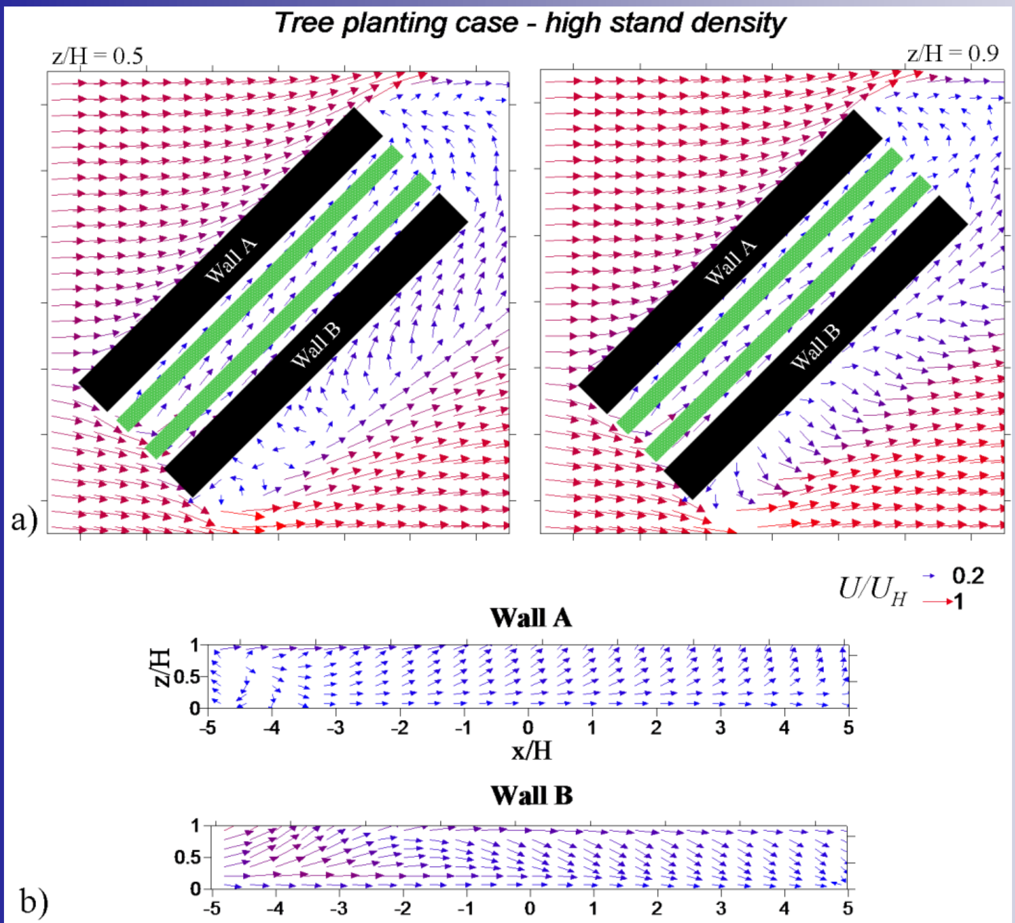
EMPTY STREET CANYON

CFD modelling

Validation studies (W/H=2)

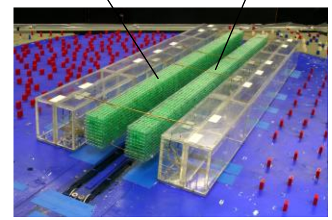
wind direction: 45°

CFD FLOW



Wall A

Wall B



street canyon model – wind tunnel

➢Concentration patterns are due to the predominant parallel flow component.

➢In particular, at the upstream entry of wall A the corner eddy found in the tree-free case does not occur anymore, due to the presence of trees which behave as obstacles

➢The helical flow vortex is also broken and, as a consequence, a wind flowing parallel to the walls is evident. However, from the figure it can be noted that wind velocities are slower than those found in the previous case. As the result of this, the pollutants released from the traffic are larger.

Study of tree-atmosphere interaction and assessment of air quality in real city neighbourhoods

Aspect ratio vs wind direction

Tree-free case

- W/H = 1: worst air quality conditions occur when the wind is perpendicular. No improvement in the 45° inclined wind direction case
- W/H = 2: the wall-averaged concentrations decrease for both the perpendicular and 45° inclined case compared to the W/H=1 case. Improvement in the 45° inclined wind case

→ The larger the aspect ratio of tree-free street canyons, the worst is the effect associated to perpendicular wind direction

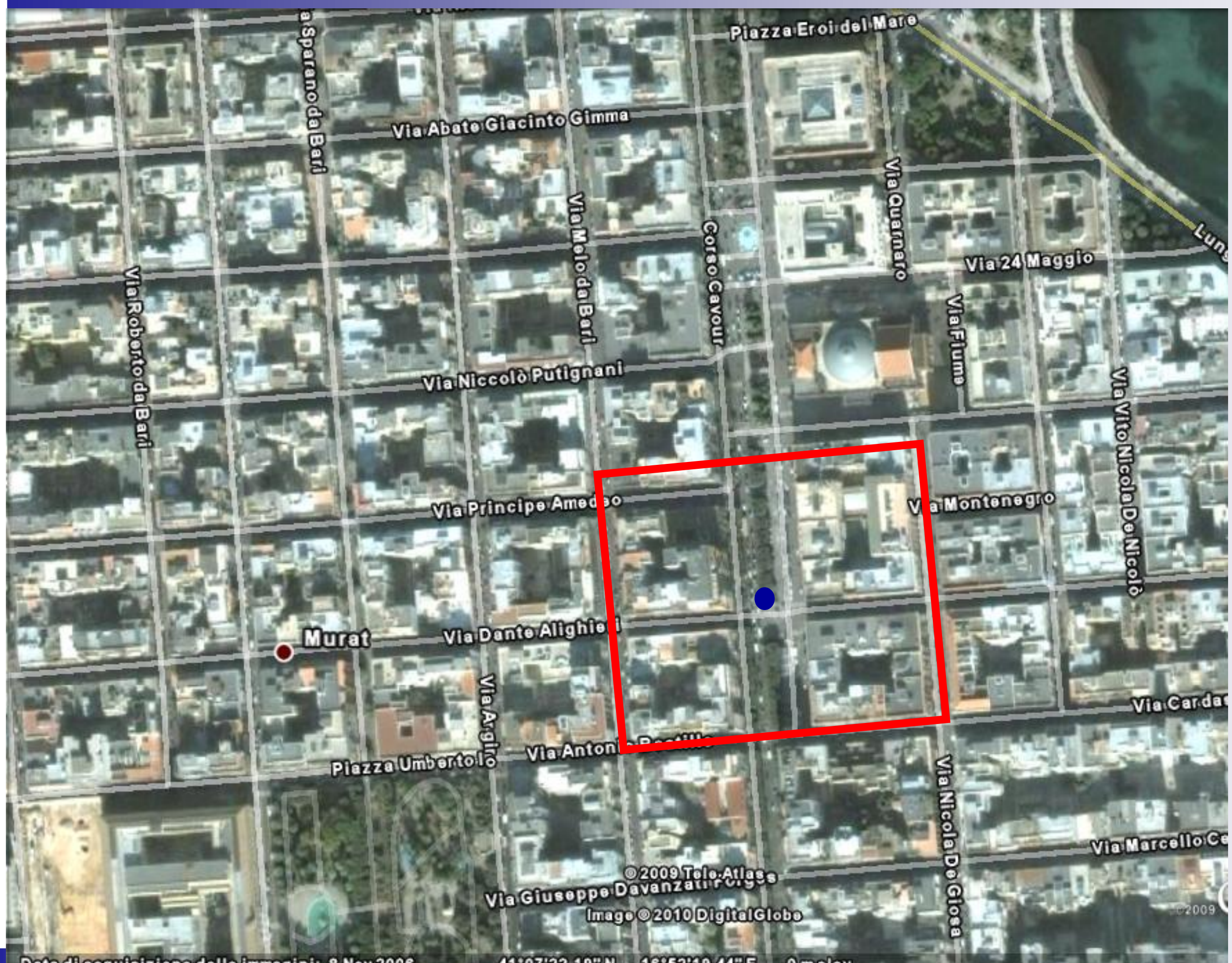
- **in the presence of trees**, the largest concentrations occur in the W/H = 1

→ As above, although increasing the aspect ratio the relative improvement associated to inclined wind directions is less evident

Study of tree-atmosphere interaction and assessment of air quality in real city neighbourhoods

REAL SCENARIOS

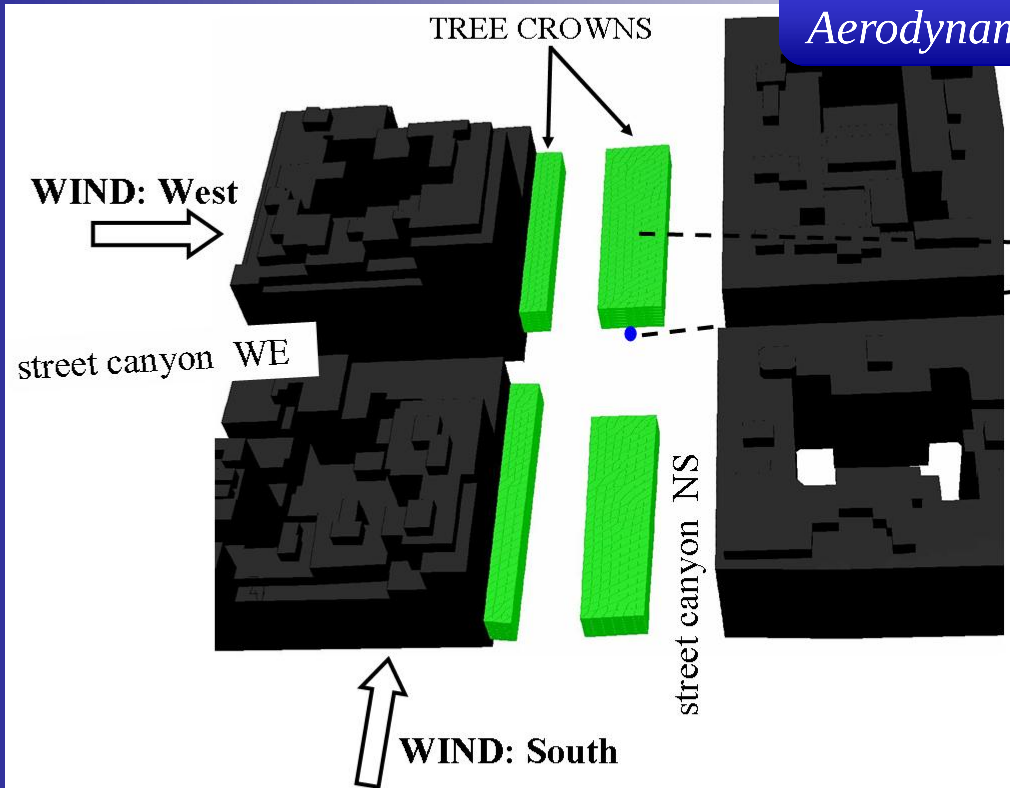
Aerodynamic effects of trees in Bari (Italy)



- 2 street canyons and 1 junction
- H_{max}~46m, H_{mean}~24m
- "repetition unit", i.e. representative of the urban texture of a larger portion of the city.
- 4 tree rows avenue-like tree planting of high stand densities, i.e. with interfering neighbouring tree crowns.

REAL SCENARIOS

Aerodynamic effects of trees in Bari (Italy)



- street canyon NS: W/H ~ 2
- street canyon WE: W/H ~ 0.5

➢Wind meandering, buoyancy effects, background concentrations and other variables limit the comparison between monitored and simulated data to a rather qualitative analysis of the concentration levels at the monitoring positions since CFD simulations are typically done assuming a constant wind direction and without thermal stratification.

➢CFD simulations aim at providing an example of how numerical tools can support city planning requirements

➢Computational cells: three millions and a half (cell dimensions $\delta x_{min} = \delta y_{min} = 1m$, $\delta z_{min} = 0.3m$ until the height of 4m).

➢4 days simulation time with 2 processors

REAL SCENARIOS

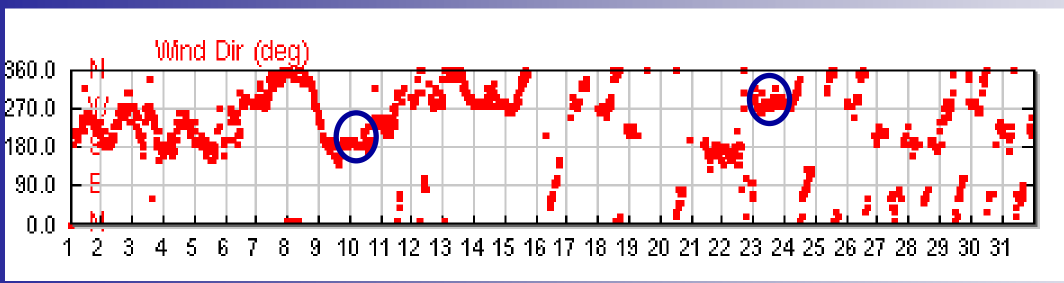
Aerodynamic effects of trees in Bari (Italy)

Concentration ratio

$$\frac{C_{west} \times U_{west}}{C_{south} \times U_{south}}$$

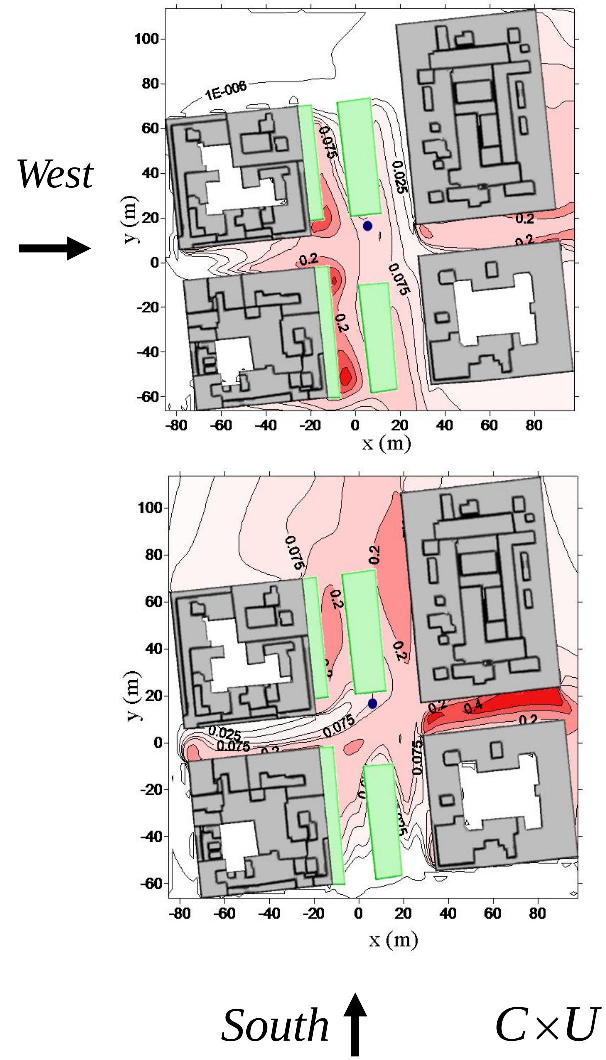
Measurements at monitoring station (~3m)

- mean daily concentration ratios ranging from ~ 1.5 to ~ 2.2 during winter/spring time in the years 2005/2006



•*10 March 2006*	•*23 March 2006*
•*Wind dir.:* ***South***	•*Wind dir.:* ***West***
•*Usouth: 3.1 m/s*	•*Uwest: 4.2 m/s*
•*Csouth.* $25 \mu g/m^3$	•*Cwest.:* $27 \mu g/m^3$

CFD simulations



Concentration ratios

~ 1.5 (MEAS.)

~ 1.1 (SIM.)

REAL SCENARIOS

Aerodynamic effects of trees in Bari (Italy)

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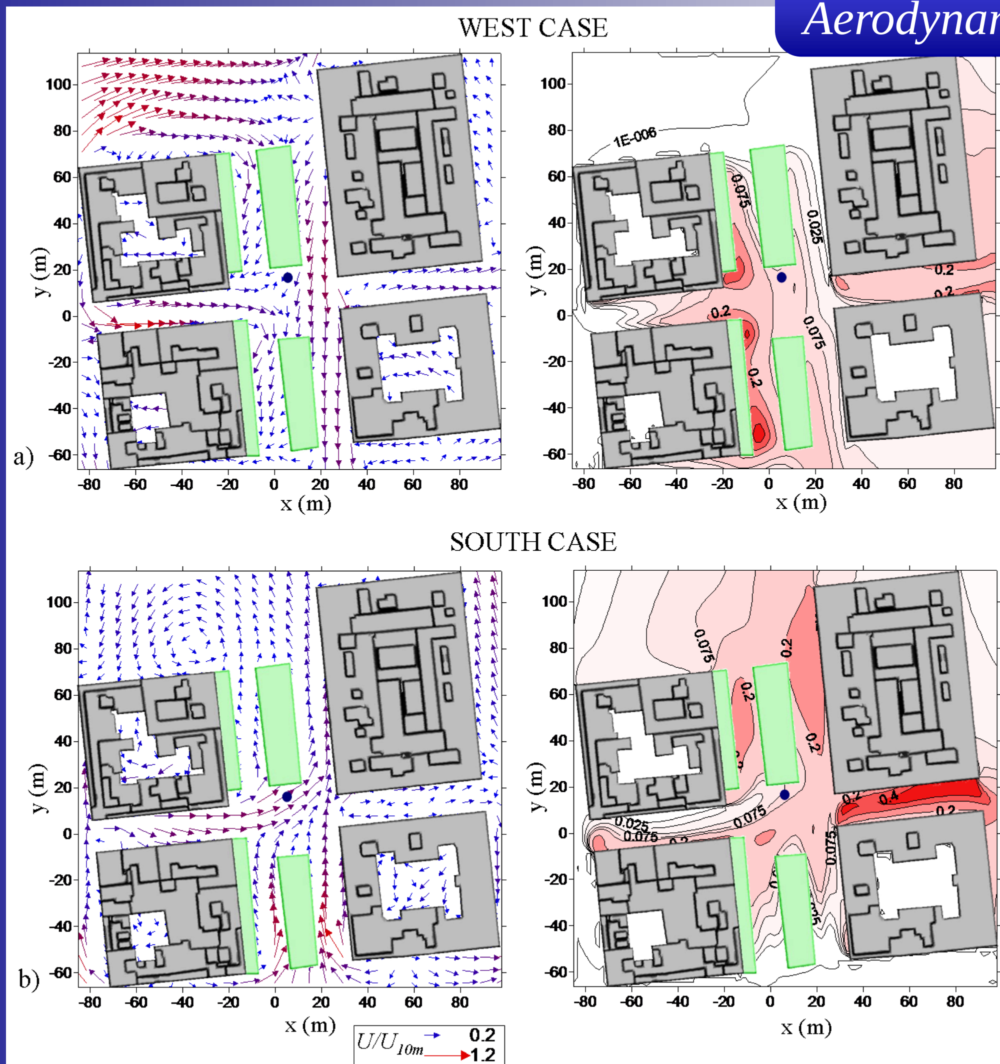

CFD results provide a basis to interpret the monitored data

➢WEST CASE: due to the interaction with the buildings and tree planting arrangement, the resulting flow is channelled along the street canyon NS (wider canyon), predominately blowing from North to South.

➢SOUTH CASE: wind blows predominately along the approaching direction which is from South to North.

REAL SCENARIOS

Aerodynamic effects of trees in Bari (Italy)

Concentration ratio

$$\frac{C_{west} \times U_{west}}{C_{south} \times U_{south}}$$

	West/South concentration ratio
Tree	Measurement: ~1.5 Simulation: ~1.1
Tree-free	Measurement: N/A Simulation: ~0.3

Without trees the situation is reversed!

WEST CASE

- **Larger velocities**
- **3 times smaller concentrations at monitoring position without trees**

SOUTH CASE

- **Slightly larger velocities (channelling along tree spaces transports more pollutant away from monitoring position)**
- **1.3 times larger concentrations at monitoring position without trees**

➢ **Simulations show that it has been crucial to consider the effect of trees on pollutant dispersion to explain qualitative difference between the two cases**

Conclusions

- Trees in urban street canyons have important **aerodynamics effects** (**aspect ratios** and **wind direction** are among the most important ones!) They have somehow been quantified using wind tunnel controlled experiments. Real conditions may be different.

- **BULK effects are probably understood individually but not in combination (especially in real scenarios)… multiple canyons, neighbourhood scale.**

- **RANS CFD** simulations/analyses for concentration predictions in street canyons **are currently feasible** with a proper turbulence closure but most probably LES is more adequate to take into account non-stationary processes (We are currently exploring this).

- **We still need to account for the effect of buoyancy (Radiation Sheltering effect but buildings release heat in. Trapping effect. Warm air in the bottom part of the canyon.**

THANK YOU

FOR

YOUR ATTENTION