MODELING URBAN METEOROLOGY OVER IDEALISED CITIES. COMPARISON BETWEEN RESULTS OF URBAN PARAMETERIZATION IMPLEMENTED IN MESOSCALE MODEL AND HORIZONTAL SPATIAL AVERAGE PROPERTIES OBTAINED USING CFD SIMULATIONS

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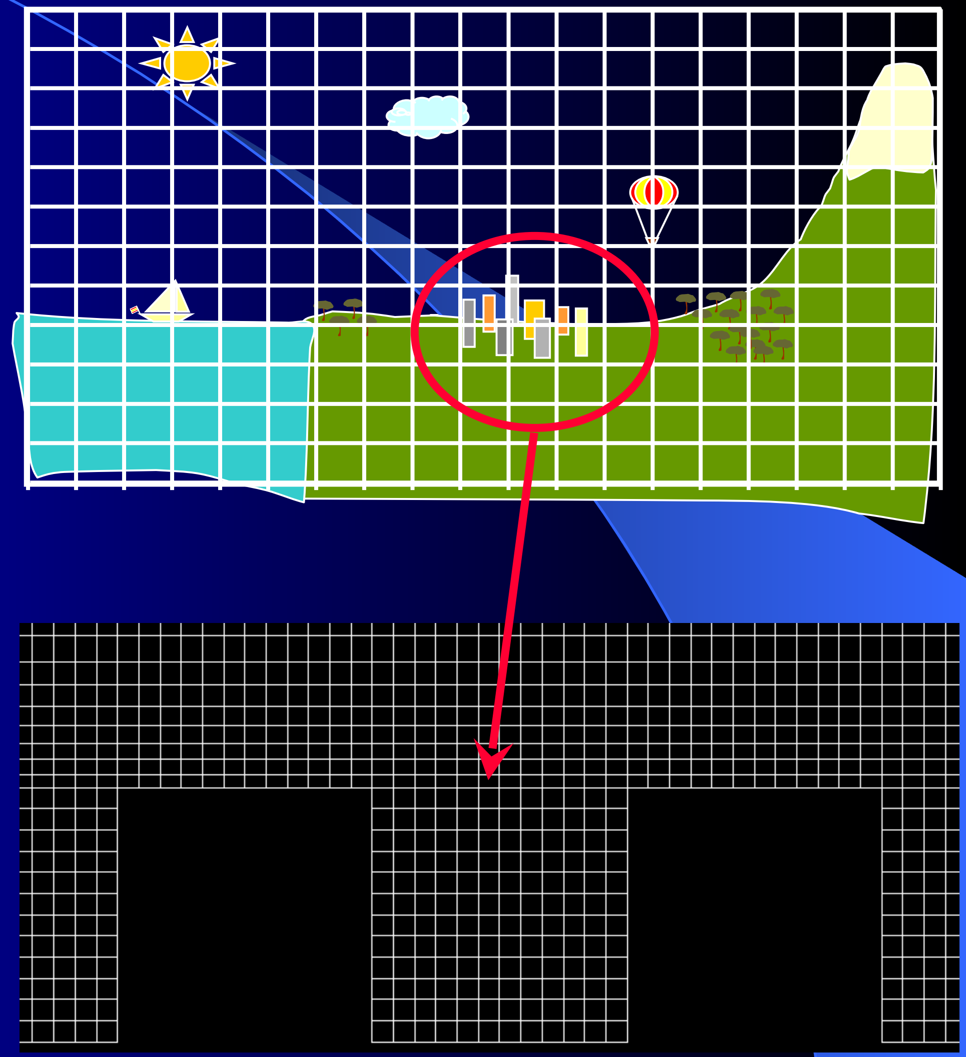
INTRODUCTION

- Resolution:
  - Mesoscale ~ km ↔ Microscale ~ m
- Simplified Urban Canopy Models:
  - Buildings are not explicitly resolved.
  - Needs Urban Parameterizations.
  - Parameterization of drag and turbulence.



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OBJECTIVES OF THE STUDY

- Focused on the mechanical effects produced by buildings.
- Evaluate urban parameterization implemented in a mesoscale model. Test case is 1-Dimension (one column of cells) simulation.
- Comparison against results of microscale simulations (Computational Fluid Dynamics, CFD).

LAYOUT OF THE STUDY

CONFIGURATION STUDIED

Staggered Array
λ = 0.25

CFD
RANS *k-ε*

Test in 1D
Mesoscale model
(FVM)

Configuration 3-D
λ = 0.25

Configuration 1-D
λ = 0.25

Results
Simulation CFD
(Building resolved)

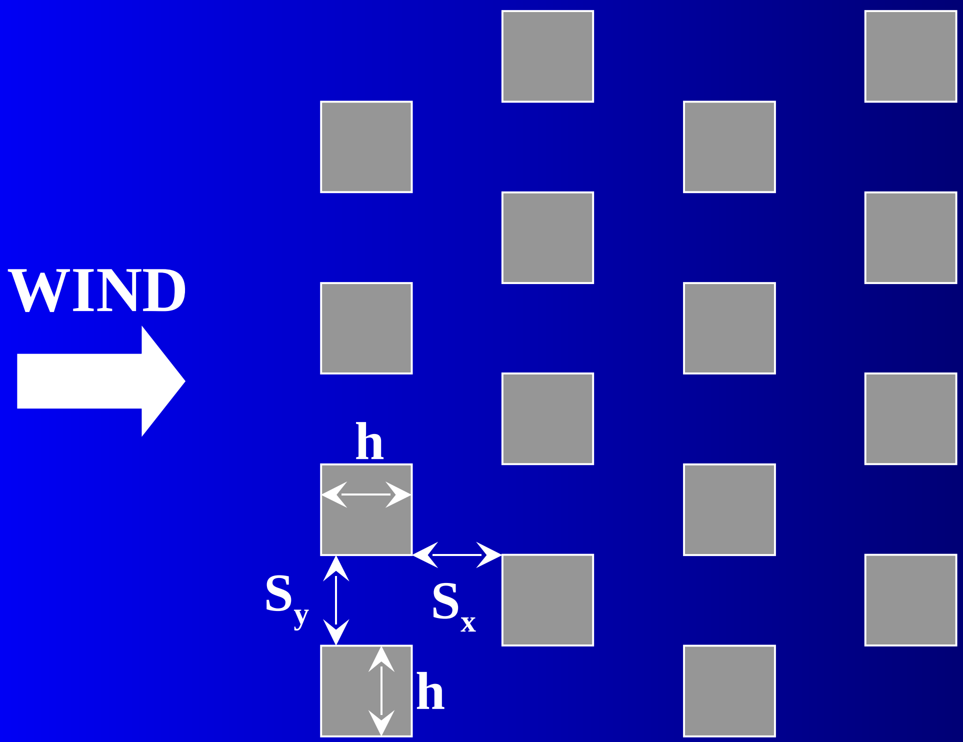
Comparison
Average Properties CFD
Vs
Results Mesoscale

Average Properties

Results for Different
Urban Parameterizations
(Martilli et al., 2002)

CONFIGURATION OF THE ARRAY

- Staggered array of cubes



- Definition of packing density

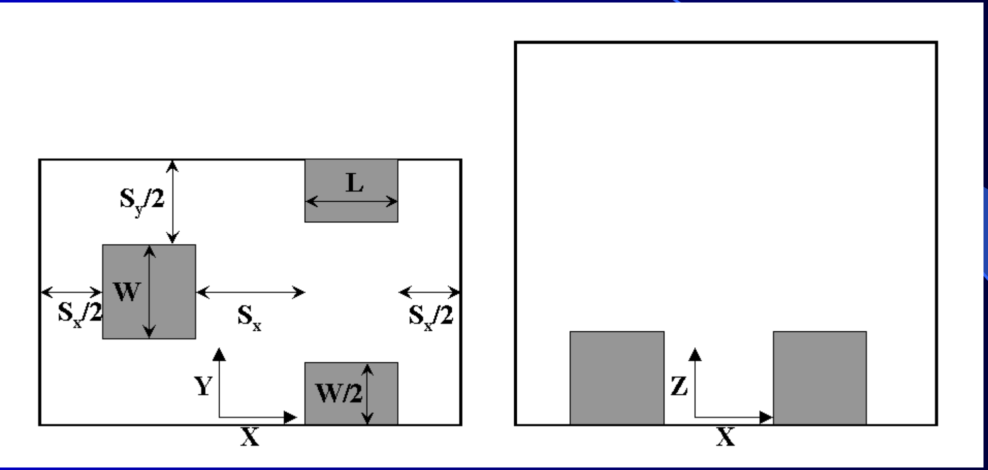
$$\lambda_f = \frac{A_f}{A_t} = \frac{h^2}{(h+S_y)(h+S_x)}$$

$$\lambda_p = \frac{A_p}{A_t} = \frac{h^2}{(h+S_y)(h+S_x)}$$

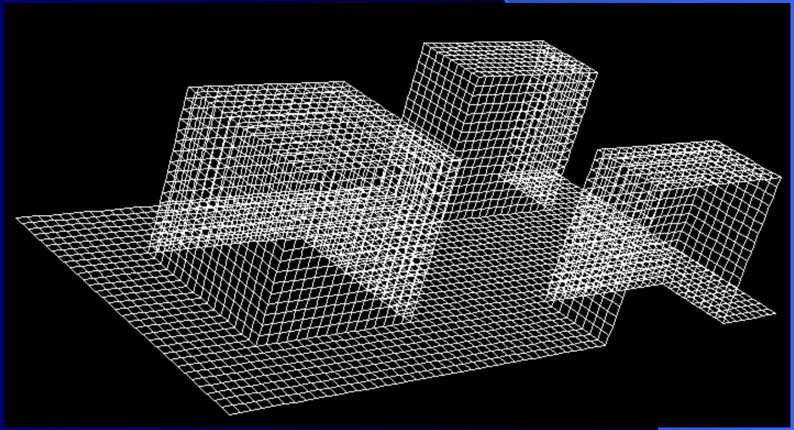
NUMERICAL DOMAIN (1)

- CFD- RANS Simulation (3-Dimensions)

WIND



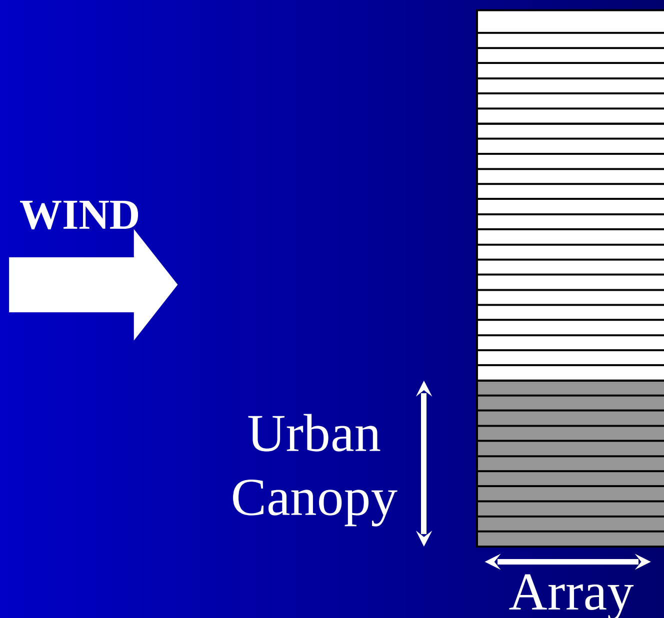
3-Dimensions



- Periodic conditions (Horizontal pressure gradient is imposed).
- Resolution in x, y and z-direction H/16

NUMERICAL DOMAIN (2)

- Test Mesoscale Urban Parameterization (1-Dimension)

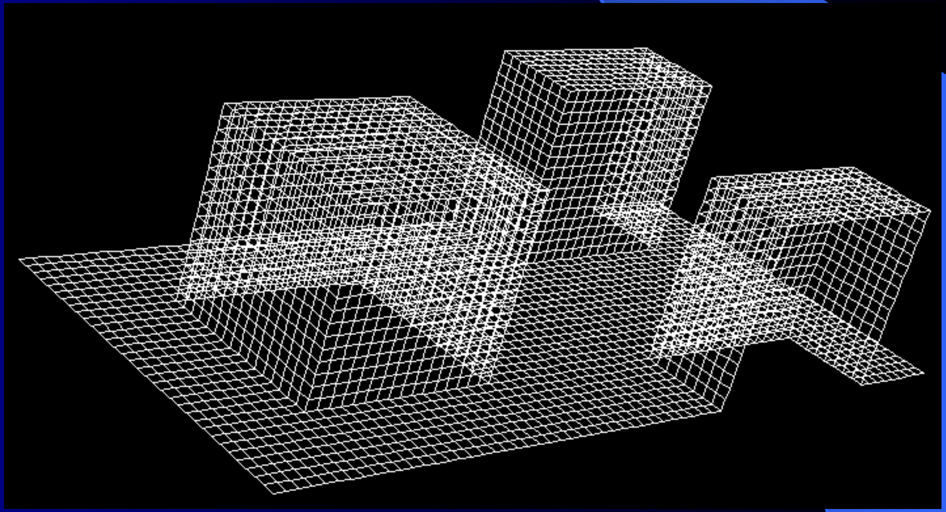


1-Dimensions

- This simulation is a test in 1-Dimension (one column of cells) using a mesoscale model with an urban parameterization.
- Resolution in vertical H/16. In horizontal only one cell represents the array of cubes (All horizontal gradients are considered 0 except a pressure gradient which is imposed).

CFD MODEL

- Reynolds Averaged Navier Stokes equations (RANS)
- Turbulence model: standard *k*-*ε*
- Steady simulations
- A uniform Cartesian mesh with 16 points per cube was used.



MESOSCALE MODEL TEST 1-D (1)

- FVM (Mesoscale model). Test in 1D (one column of cells):
  - Urban Parameterization Martilli et al. (2002).
  - K-theory, (A mean part, a turbulent part):

$$\overline{wa} = -K_z \frac{\partial A}{\partial z}$$

  - k-l turbulent closure Bougeault & Lacarrere (1989)

$$K_z = C_k l_k TKE^{1/2}$$

$$l_k = \alpha \cdot \max(z - D, h - D) \qquad l_\varepsilon = \beta \cdot \max(z - D, h - D)$$

C_k is constant (=0.4)
l_k is a length scale of turbulent kinetic energy
l_ε is defined in the dissipation term of the turbulent kinetic energy equation
TKE is the turbulent kinetic energy.
α (=1.0), β(=0.47) and D (displacement height, depends on λ) are model parameters. The values used are derived from the analysis of the CFD results.

MESOSCALE MODEL TEST 1-D (2)

- Parameterization the urban area is treated as a porous medium modelled in terms of a distributed drag force.
- The exchange of momentum on building walls due to pressure and viscous drag forces is parameterised as,

$$\mathrm{DragTerm}_n = C_n \cdot C_{drag} \cdot |U_n| \cdot U_n$$

C_n is the vertical surface building density (facing the wind) at level n

U_n is the wind speed orthogonal to street direction at level n

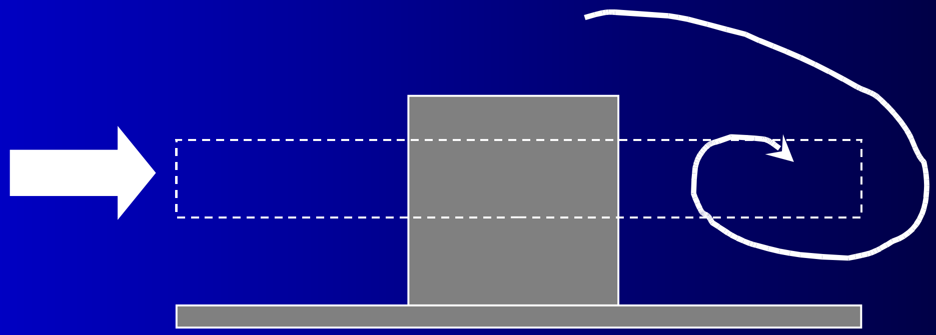
C_{drag} is the sectional drag coefficient.

- In most of the urban parameterizations (and also in this one) Cdrag is set as a constant value (in this parameterization, 0.4). However, it is well known that this parameter depends on z and on the array packing density and layout. In this study, the importance of the value chosen for Cdrag is shown. In addition, tests are shown with another parameterization of the drag force.

AVERAGING TECHNIQUE

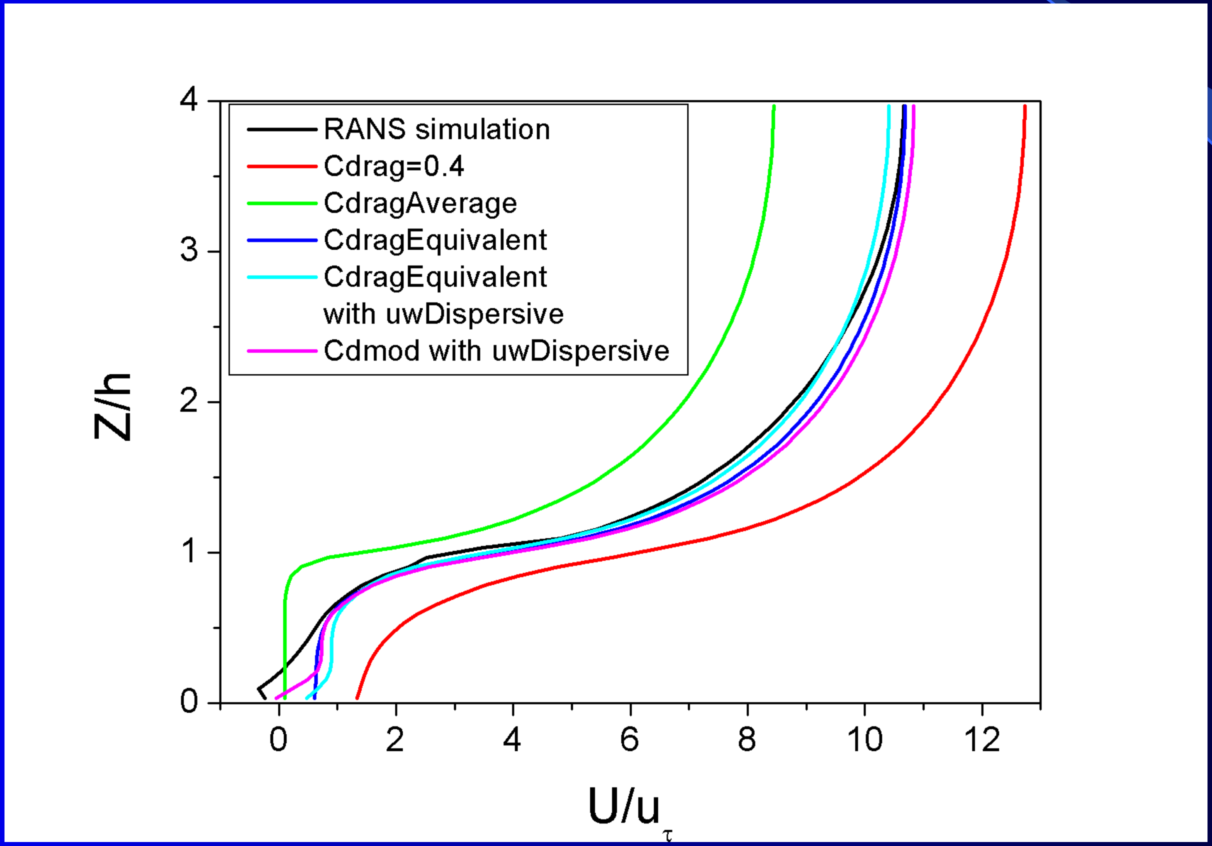
- For comparison Mesoscale – CFD, CFD results have to be horizontally averaged.
- At given z, one plane X-Y of the CFD simulation corresponds to one cells at the same height of the 1-D simulation.

$$<\overline{\psi}>=\frac{1}{V_{air}}\int_{Vair}\overline{\psi}(\vec{x},t)d\vec{x}$$



RESULTS (1)

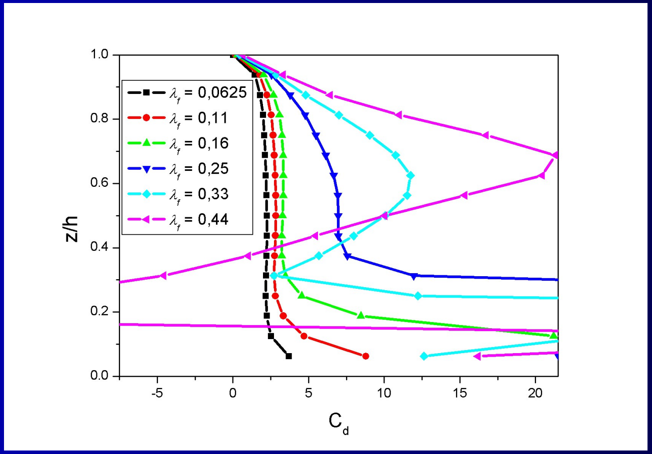
Mean Streamwise Wind Speed Profile (U / u_τ)



RESULTS (2)

Simulation 1 (Red curve)

- The urban parameterization is used with the standard value of the $C_{drag} = 0.4$. The problem is that this value depends on the configuration and packing density of the array and for a given configuration also changes with z, but it is considered constant in the parameterizations.

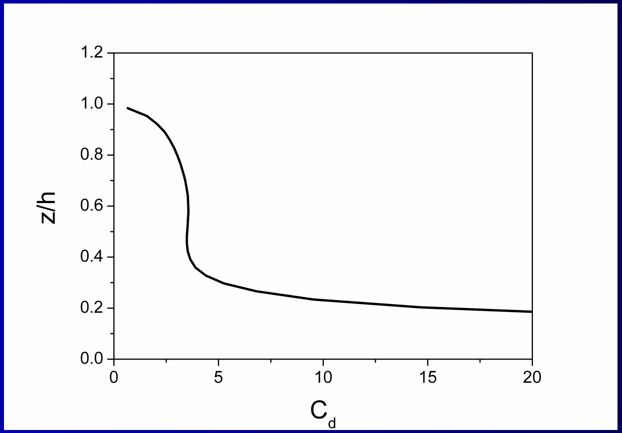


Santiago et al. (2008)

RESULTS (3)

Simulation 2 (Green curve)

- Same as 1 but using the value of the Cdrag averaged inside the urban canopy obtained in the CFD-RANS simulations (C_{drag} = 52.5). The problem in this case is that Cdrag is not constant with height taken very large values close to the ground (U is almost 0 close to the ground).



Santiago et al. (2008)

RESULTS (4)

Simulation 3 (Blue curve)

- Same as 1 but changing the value of the C_{drag} for other value (C_{dequiv}=1.78). This C_{dequiv} is computed making two consideration:
  - Constant with height
  - Drag force integrated in the whole urban canopy using Cdequiv must be correctly computed (see equation below).
- This value depends on the configuration and packing density of the array and is calculated from CFD-RANS simulation results.

$$C_{dequiv}(\lambda_f) = \frac{\tau}{\frac{1}{2}\rho \cdot \frac{1}{h}\int_0^h < \overline{U}(z,\lambda_f) > \left| < \overline{U}(z,\lambda_f) > \right| dz}$$

RESULTS (5)

Simulation 4 (Cyan curve)

- Same as 3 but with the addition in the momentum equation of a vertical profile of the dispersive stress computed with the results of the RANS simulation.

$$\psi'(x,t) = \psi(x,t) - \overline{\psi}(x) \qquad \tilde{\psi}(x) = \overline{\psi}(x) - \langle \overline{\psi} \rangle \qquad \psi(x,t) = \langle \overline{\psi} \rangle + \psi'(x,t) + \tilde{\psi}(x)$$

$$\langle \tilde{u}\tilde{w} \rangle_k = \frac{1}{N} \sum_i \sum_j \left(\overline{w}_{i,j,k} - \langle \overline{w} \rangle_k \right) \left(\overline{u}_{i,j,k} - \langle \overline{u} \rangle_k \right)$$

- Dispersive stress: transport due to time-averaged structures smaller than the size of the averaging volume.
- Usually it is not taken into account in urban parameterization.

RESULTS (6)

Simulation 5 (Purple curve)

- Same as 3 but changing the C_{drag} for C_{dmod} that takes into account the TKE and DKE (dispersive kinetic energy) and it is relatively constant with the height (Martilli and Santiago, 2007 and Santiago et al., 2008). The DKE is computed with the results of the RANS simulation and added to the urban parameterization. In this case C_{dmod} = 0.64.

$$\Delta p(z) = \frac{1}{2}\rho \cdot \langle \overline{U} \rangle^2 (z) \cdot C_d(z) = \frac{1}{2}\rho \cdot q(z) \cdot C_{d\,\mathrm{mod}}$$

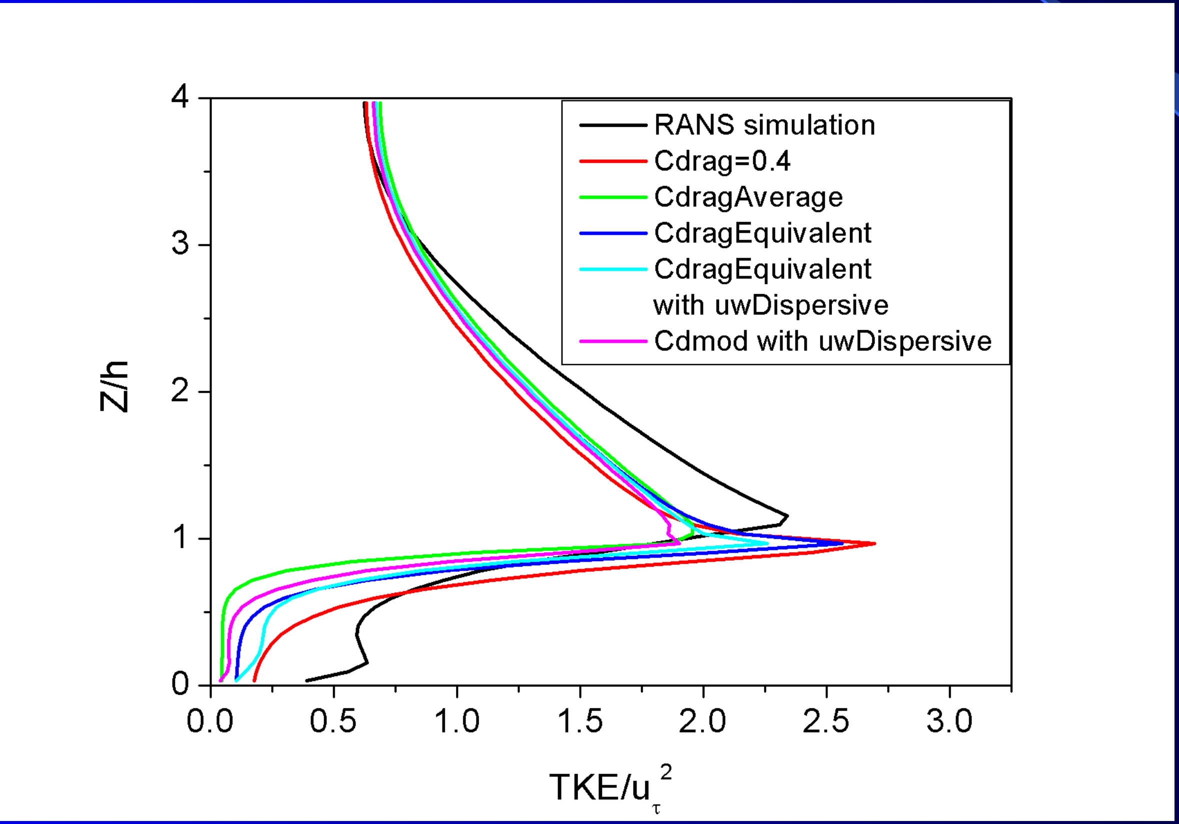
$$DKE = 0.5(<\tilde{u}^2> + <\tilde{v}^2> + <\tilde{w}^2>)$$

- DKE: kinetic energy of time averaged structure smaller than the grid cell.

$$\tilde{\psi}(x) = \overline{\psi}(x) - <\overline{\psi}> \qquad v_{TKE}^2 = 2TKE \qquad v_{DKE}^2 = 2DKE \qquad q_{tot} = <\overline{U}>^2 + v_{TKE}^2 + v_{DKE}^2$$

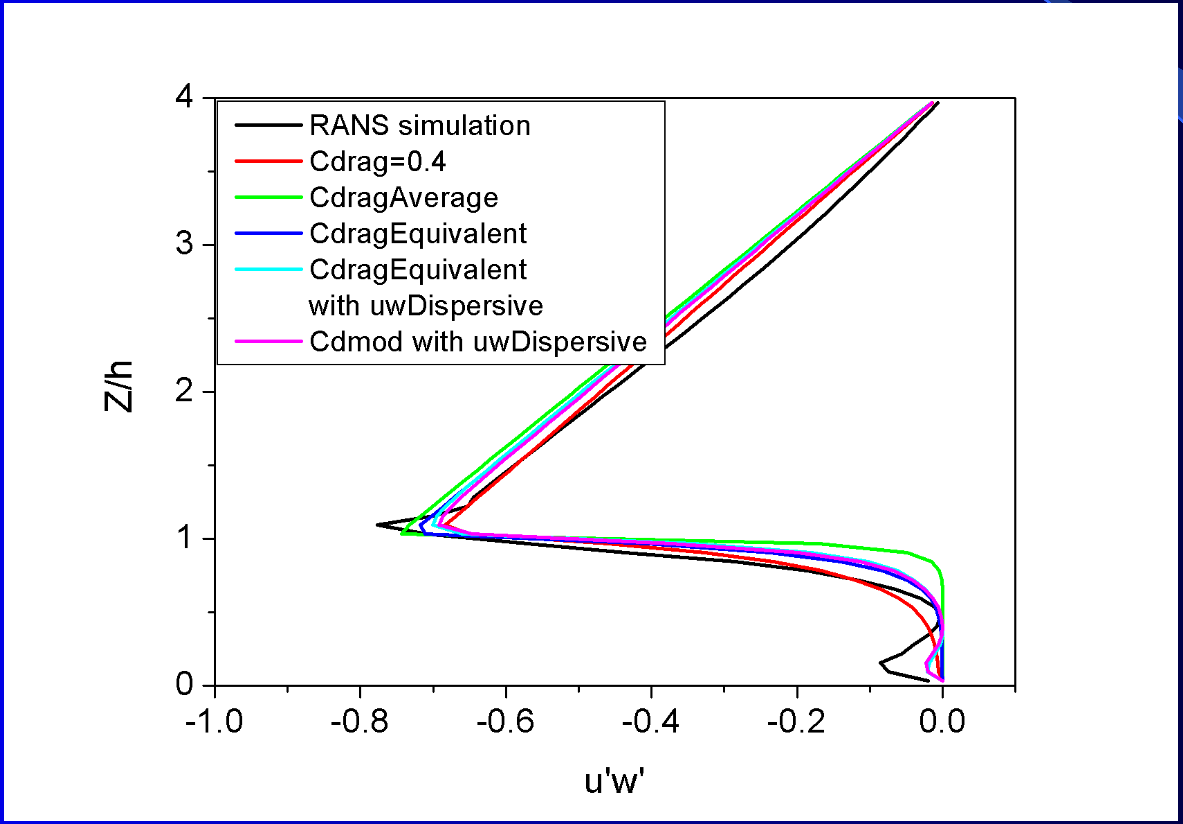
RESULTS (7)

Turbulent Kinetic Energy (TKE / u_τ^2)



RESULTS (8)

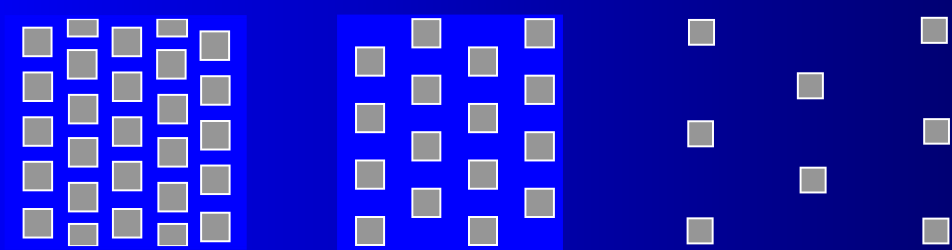
Shear Stress ($\overline{u'w'}/u_\tau^2$)



RESULTS (9)

- Some parameters of the urban parameterization (α and β) were fitting for λ = 0.25.
- There are other variables depending on geometrical configurations (input):
  - D (displacement height)
  - Drag coefficients (in this case C_{dequiv} was used)
- Other packing densities were used to test the model.
- The values of D and C_{dequiv} used for urban parameterization simulations are computed from CFD results.

λ = 0.44 λ = 0.25 λ = 0.0625

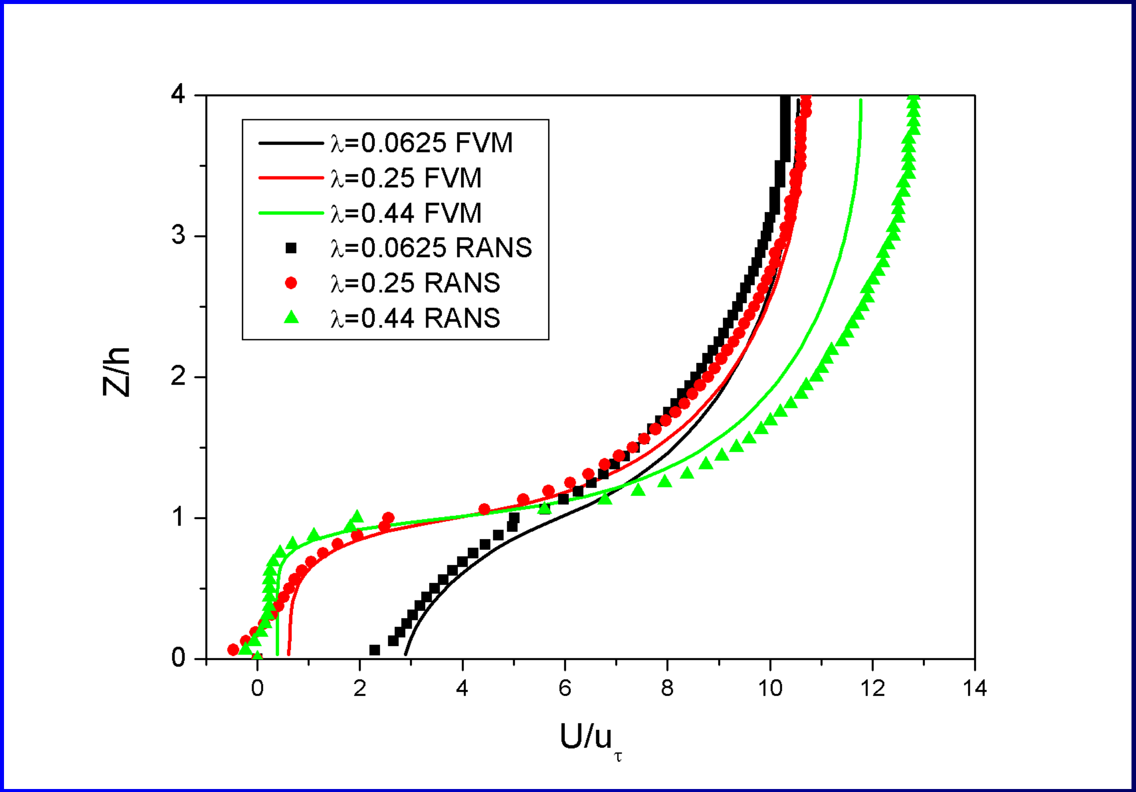


$$\lambda_f = \frac{A_f}{A_t} = \frac{h^2}{(h+S_y)(h+S_x)}$$

$\boxed{C_{dequiv}}$

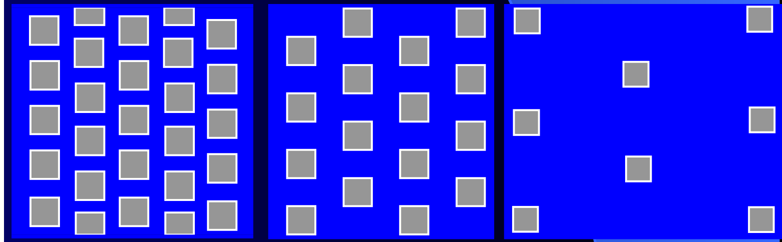
RESULTS (10)

- These results are for C_{dequiv}.
- The results of urban parameterization follows the tendency of CFD wind profiles.



$$\lambda_f = \frac{A_f}{A_t} = \frac{h^2}{(h+S_y)(h+S_x)}$$

λ = 0.44 λ = 0.25 λ = 0.0625



SUMMARY AND CONCLUSIONS

- Using this urban parameterization with the input computed from CFD simulations (Drag coefficients and D), vertical profiles of average variables from CFD simulations are reproduced by 1D test of the urban parameterization coupled with mesoscale model.
- These simulations have shown the importance of drag parameterization and the value of the C_{drag} that it is usually considered as a constant in the urban parameterizations.
- In future works, other packing densities and other configurations will be studied in order to find suitable values of the sectional drag coefficients and parameterise other variables such as dispersive stress.

Thank you for your attention