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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Abstract: Air quality inside the urban canopy layer (UCL) is important because here is where people live and a significant part of the emissions are located. In this way, the modeling of UCL is also important. Different factors such as the increase of urban population and the improvement of computational power, has produced an increasing interest on urban mesoscale modeling since mid 1990s. However, the modeling of urban boundary layer is difficult because it is influenced by the complex morphology of a city (buildings, cars, gardens) with different mechanical and thermal/radiative properties. In addition, the domain of mesoscale models has a horizontal extension of several tens of kilometers (the whole city and its surrounding area) and, for computational reasons, it is not possible to solve explicitly the flow around buildings. Therefore, urban parameterizations are necessary for high resolution mesoscale simulations. On the other hand, Computational Fluid Dynamics (CFD) models can solve explicitly the flow around buildings but their simulation domains cannot cover the whole city. In this work, focused on mechanical effects produced by buildings, CFD simulations and the horizontal spatial average of the different flow properties are used to assess the performance of an urban parameterization implemented on a mesoscale model and find its strengths and weaknesses. Horizontal spatial average of the CFD results around the buildings are made in order to compare with similar mesoscale variables corresponding to a column of computational cells over a urban zone with the same characteristics as the CFD configuration. In this case, the city is represented by an array of cubes.

Key words: *CFD Model, Mesoscale Model, Urban Canopy, Urban Parameterization.*

1. INTRODUCTION

The impact of the city on the urban wind simulated by a mesoscale model can be considerable. These models use parameterization to simulate the effect of urban zones. In this way, the objective of this study is to evaluate the performance of the urban parameterization implemented on a mesoscale model using results of microscale model (CFD model). The CFD models use better resolution and solve the wind around building explicitly. Hence horizontal spatial average of CFD results are compared with the results of the mesoscale simulation using the urban parameterization.

2. CASE CONFIGURATION

In this study, the city is represented by a staggered array of cubes (Fig. 1). The packing density is characterised by the non-dimensional ratios λ_f and λ_p. defined in equation (1) and (2).

$$\lambda_f = \frac{A_f}{A_t} = \frac{hW}{(W+S_y)(L+S_x)} \quad (1)$$

$$\lambda_p = \frac{A_p}{A_t} = \frac{LW}{(W+S_y)(L+S_x)} \quad (2)$$

where h, W and L are the dimensions of the obstacles. In this case, the obstacles are cubes and $h = W = L$. In the configuration studied $S_x = S_y = h$ (Fig. 1). Hence, $\lambda_f = \lambda_p = 0.25$.

The staggered array of cubes (Fig. 1) is simulated using a CFD model and a 1D version of a mesoscale model with an urban parameterization described in the next sections.

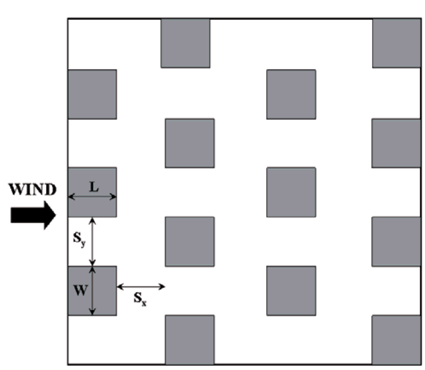

Figure 1. Plan view of the array of cubes studied.

3. CFD SIMULATIONS

CFD simulation is performed using the CFD model FLUENT. The simulations are based on the steady state Reynolds Averaged Navier-Stokes (RANS) equations and the standard k-ε turbulence model. The domain height is $4h$, where h is the height of the cubes. The domain is shown in Figure 2. Symmetric boundary conditions are imposed in the spanwise direction. Periodic boundary conditions are imposed in the streamwise direction to simulate an infinite array (Fig. 1), and the flow is driven by a pressure gradient equal to $\rho u_\tau/4h$, where $u_\tau = 0.45\ \mathrm{ms}^{-1}$. A uniform Cartesian grid is used, with each cube being resolved by 16 grid points in each direction (i.e. resolution is $\Delta x = \Delta y = \Delta z = h/16$). More information concerning CFD simulation is shown in Santiago, J.L. et al. (2008).

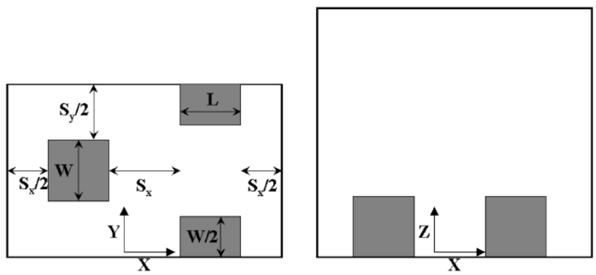

Figure 2. Plan view and vertical view of the CFD simulation domain.

4. MESOSCALE SIMULATIONS

The mesoscale simulations are performed using a 1D version of the Finite Volume Model (FVM) (Clapier, A. et al., 1996) with the urban parameterization described by Martilli, A. et al. (2002). In this model, above the ground, the vertical fluxes due to turbulent transport, are computed using the K-theory approach,

$$\overline{wa} = -K_z \frac{\partial A}{\partial z} \tag{3}$$

where A is the mean part and a is the turbulent part of a variable. In order to calculate the diffusion coefficient, K_z, a k-l turbulent closure based on Bougeault, P. and P. Lacarrere (1989) is used. The diffusion coefficient is computed as follows

$$K_z = C_k l_k TKE^{1/2} \tag{4}$$

where C_k is constant (=0.4), l_k is a length scale of turbulent kinetic energy and TKE is the turbulent kinetic energy.

In addition, other length scale (l_ε) is defined in the dissipation term of the turbulent kinetic energy equation.

This study focuses on the "dynamical" part (impact on the wind field and turbulence). The thermal part is not accounted for (neutral atmosphere, no heat fluxes from the buildings and ground). Based on an analysis of the CFD results, the length scales are modified, and parameterized with the following expressions,

$$l_k = \alpha \cdot \max(z - D, h - D) \tag{5}$$

$$l_\varepsilon = \beta \cdot \max(z - D, h - D) \tag{6}$$

where α, β and D are model parameters. The values used, derived from the analysis of the CFD results are $\alpha = 1.0$, $\beta = 0.47$. D is related to the displacement height of the wind velocity profile and depends on the packing density. For this case (staggered configuration with $\lambda_f = \lambda_p = 0.25$) $D = 0.86$, as it was computed from the wind profile obtained in the CFD simulation.

Another important issue is the drag force. This parameterization treats the urban area 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,

$$\mathrm{DragTerm}_n = C_n \cdot C_{drag} \cdot |U_n| \cdot U_n \tag{7}$$

where 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 and C_{drag} is the sectional drag coefficient. In most of the urban parameterizations (and also in this one) C_{drag} 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 C_{drag} is shown. In addition, tests are shown with another parameterization of the drag force.

In this case, the mesoscale model is run in 1D mode, e. g. the domain is a vertical column of computational cells over an urban zone with the same characteristics as the CFD configuration (i.e. one cell in the mesoscale domain corresponds to a large number of cells located at horizontal plane in the microscale domain) (Figure 3). The flow is also driven by an horizontal pressure gradient.

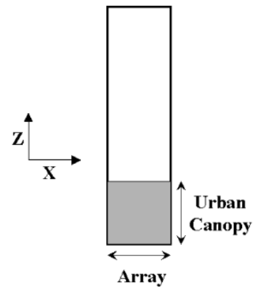

Figure 3. Mesoscale simulation domain.

5. AVERAGING TECHNIQUE

In atmospheric modelling over urban environment, it is impossible, for computational reasons, to have a domain large enough to contain the whole city and its surrounding areas and to have a resolution high enough to solve explicitly all the buildings of the city. For this reason, the accuracy of the urban parameterization used to account the effect of the buildings on the spatially averaged (over the grid cell volume of the mesoscale models) variables plays an important role in the modelling process. In this way, CFD models are important tools for this objective. They provide results with high enough spatial resolution to compute accurate values of the average variables (Martilli, A. and J.L. Santiago, 2007). As described above, the horizontal dimensions of the domain used are very different for mesoscale and mircroscale simulations. In order to solve the effect of building explicitly, the number of cell in the horizontal directions are 64 (x-direction) x 32 (y-direction), while the mesoscale domain is only a vertical column of cells (i.e. only one cell in horizontal directions).

Using the domains described in the previous section, the spatial averages made over CFD volumes are representative of a grid cell of a mesoscale model (usually of the order of few kilometres or several hundreds meters). In this case, the CFD model provides time-(or ensemble-) averaged values (indicated by an overbar) and the spatial averaged values can be seen as space averages of the time- (or ensemble-) averaged fields. The spatial average of a variable ψ can be defined as,

$$< \psi > = \frac{1}{V_{air}} \int_{Vair} \psi(\bar{x},t) d\bar{x} \tag{8}$$

In this work, the horizontal spatial averages are made over thin slices at different heights (Fig. 4). By comparing the results from two models, the performance of the urban parameterization of the mesoscale model can be analysed. The variables averaged from the CFD results are streamwise velocity (<U>), turbulent kinetic energy (<TKE>), Reynolds stress ($<\overline{u'w'}>$) and they are compared with the corresponding ones from the mesoscale model.

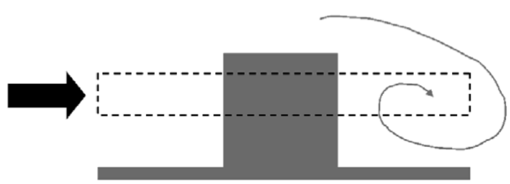

Figure 4. Diagram of the horizontal spatial averaged.

In the averaging of the RANS equations, appears the so-called dispersive stress defined in equation (9).

$$\tilde{u}\tilde{w}_{ij} = \left(< \bar{u} > - \bar{u}_{ij}\right)\left(< \bar{w} > - \bar{w}_{ij}\right) \tag{9}$$

It is related to the transport due to time-averaged structures smaller than the size of the averaging volume. More details concerning dispersive stress can be found in Martilli, A. and J.L. Santiago (2007). This process is not usually incorporated in the urban parameterizations, and it can be important in some situations. In this study, this process is calculated from CFD results and the values are added to the mesoscale simulation.

6. RESULTS

Vertical profiles of the average properties computed from the CFD-RANS simulation are compared with the vertical profiles obtained from mesoscale simulations using the urban parameterization with different modifications. Five mesoscale simulations have been performed. The differences among them are:

Simulation 1: 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 (Red curve in Fig. 5, 6, 7).

Simulation 2: Same as 1 but using the value of the C_{drag} averaged inside the urban canopy obtained in the CFD-RANS simulations (C_{drag} = 52.5). The problem in this case is that C_{drag} is not constant with height taken very large values close to the ground (U is almost 0 close to the ground) (Green curve).

Simulation 3: 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. Firstly it must be constant with height, and secondly the drag force integrated in the whole urban canopy using C_{dequiv} must be correctly computed (see equation 10). This value depends on the configuration and packing density of the array and is calculated from CFD-RANS simulation results (Blue curve).

$$\frac{1}{h}\int_0^h C_{drag}(z,\lambda_f) < \overline{U}(z,\lambda_f) > \left| < \overline{U}(z,\lambda_f) > \right| dz = C_{dequiv}(\lambda_f) \cdot \frac{1}{h}\int_0^h < \overline{U}(z,\lambda_f) > \left| < \overline{U}(z,\lambda_f) > \right| dz \qquad (10)$$

Simulation 4: 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 (Cyan curve).

Simulation 5: 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. More information about C_{dmod} can be found in Martilli, A. and J.L. 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(Purple curve).

Vertical profiles of *U*, *TKE* and shear stress obtained from the five mesoscale simulations and the variables averaged from the RANS results are shown in Figures 5, 6 and 7. The *U* profiles of simulations 3, 4 and 5 are similar above the canopy. In the bottom part of the canopy, there are some differences. A smoother increase of velocity (more similar to the RANS results) is observed when the dispersive stress is taken into account. However, the simulations 1 and 2 show behaviours far away from the RANS velocity profile. In the simulation 1, the drag force is underpredicted, hence the wind speed is overestimated. The opposite case happens in the simulation 2. This fact shows the importance to use a suitable value of the C_{drag} or other suitable parameterization for the drag force in the momentum equations. Concerning the *TKE* and the shear stress there are not high differences among the simulations, especially the shear stress is well predicted. *TKE* is underpredicted in the bottom part of the canopy and the height of its maximum is slight underpredicted in comparison with the RANS simulation.

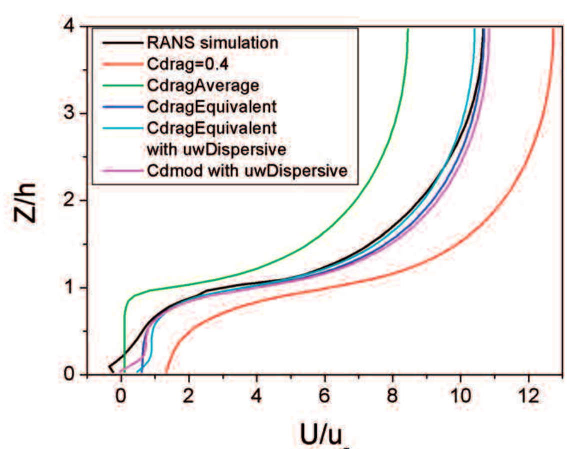

Figure 5. Vertical profile of the normalised streamwise velocity (U/u_τ) for the microscale simulation and mesoscale simulations.

7. CONCLUSIONS

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 addition, the effect of the dispersive stress inside the canopy has been observed.

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.

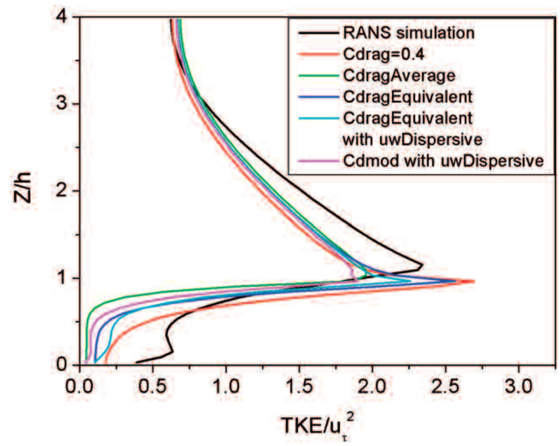

Figure 6. Same as Figure 5 but for turbulent kinetic energy normalised (TKE/u_τ^2).

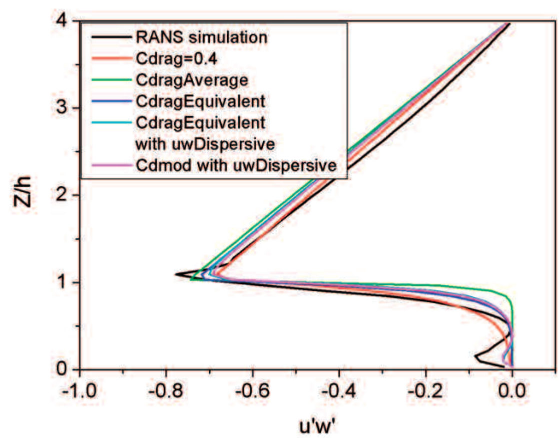

Figure 7. Same as Figure 5 but for shear stress normalised ($\overline{u'w'}/u_\tau^2$).

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