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PARAMETERIZATION OF DRAG FORCES IN URBAN CANOPY MODELS USING MICROSCALE-CFD MODELS FOR DIFFERENT WIND DIRECTIONS

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Abstract: In mesoscale modelling, Urban Canopy Parameterizations (UCP) are used to take into account the effect of urban morphology (building, trees,...) on the spatially averaged fluxes and mean variables. UCPs do not resolve the flow around the urban obstacles but provide an approach that is a compromise between simplicity and accuracy. However, some aspects of UCP have not been studied in depth and it is necessary to analyse them. This work is focused on the study of drag parameterisation inside the UCP for cases with inlet wind not orthogonal to the buildings. For this task, Computational Fluid Dynamic (CFD) models are used to simulate simple cases with different wind directions and their results are used to improve and to check the performance of a UCP.

Key words: *Drag coefficients, Direct numerical simulations (DNS), Reynolds-averaged Navier-Stokes (RANS), Urban canopy parameterization***.**

INTRODUCTION
Modelling the Urban Canopy Layer (UCL) is very important for many applications in air quality and urban climate, but the atmospheric processes involved are complex due to strong heterogeneities of urban morphology. The scale of these processes ranges from the size of urban obstacles (few meters) to the size of the whole city. Some applications need to take into account the whole range of scales, but for a domain that cover the whole city (mesoscale domain) the resolution, for computational reasons, can not be high enough to resolve explicitly the flow around buildings. Then, the complex flow patterns inside streets generated by the interaction of buildings with wind should be parameterised. In mesoscale modelling a compromise between simplicity and accuracy is needed and Urban Canopy Parameterizations (UCP) provide a suitable approach. However, some assumptions and input parameters of UCP have not been studied in depth and should be revised. For example, a suitable drag force parameterization is important to reproduce correctly the mean spatially averaged flow field inside urban canopy, especially when the incident wind is not orthogonal to buildings.

In this work, the use of computational fluid dynamics (CFD) models that solve explicitly the flow around obstacles (resolution ~ m) to improve UCPs is proposed. Scenarios with different inlet wind directions are simulated over an array of cubes by a CFD model. The main features of the mean flow are analysed and these microscale results are used to look for a suitable parameterization of drag forces in a UCP. These cases are also simulated by using UCP with the new drag force parameterizations.

The paper is organised as follows: firstly, a brief description of models, set-ups and methodology is made. Secondly, the main flow features and spatial average properties are analysed. Finally, a parameterisation of drag forces inside a UCP is proposed and checked against spatial average results from CFD models.

MODELS DESCRIPTIONS, METHODOLOGY AND SET-UPS
Reynolds-averaged Navier-Stokes (RANS) models are used to perform a set of simulations over an array of cubes with different inlet wind angle. The turbulence scheme used is standard k-ε. Previously, some of these simulations are compared against Direct Numerical Simulations (DNS) in order to check their accuracy. RANS presents some limitations but we consider that they are the best compromise between accuracy and computations (Santiago, J.L. et al., 2008 and Santiago, J.L. and A. Martilli, 2010).

However, for mesoscale applications it is necessary to used UCPs. In this case, we use 1D version of the multilayer UCP developed by Martilli, A. et al. (2002) and modified by Santiago, J.L. and A. Martilli (2010). The focus is the dynamical effects induced by urban surfaces. We propose to use CFD results to: 1) derive parameterizations of drag forces and 2) evaluate 1-D UCP schemes. The methodology is similar to that followed by Santiago, J.L. and A. Martilli (2010).

In this study, the city is represented by an array of aligned cubes with $\lambda_f = \lambda_p = 0.25$ (i.e. the height of the cubes is equal to the separation between them). Different inlet wind directions (RANS: 0º, 7º, 14º, 20º, 26.6º, 30º, 35º, 40º, 45º, DNS: 0º, 14º, 26.6º) are simulated over this configuration. For CFD models (DNS and RANS) periodic conditions are set at lateral boundaries to reproduce an infinite array. The flow is driven by a horizontal pressure gradient. A Cartesian grid is used, with each cube being resolved by 16 and 32 grid points in each direction by RANS and DNS simulation respectively. A test about grid independence of results was made, and it has shown that these resolutions are acceptable.

UCP is run in 1-D mode, i.e. the domain is a vertical column of computational cells over an urban zone (16 levels to resolve the building). A scheme of the domain is shown in Figure 1.

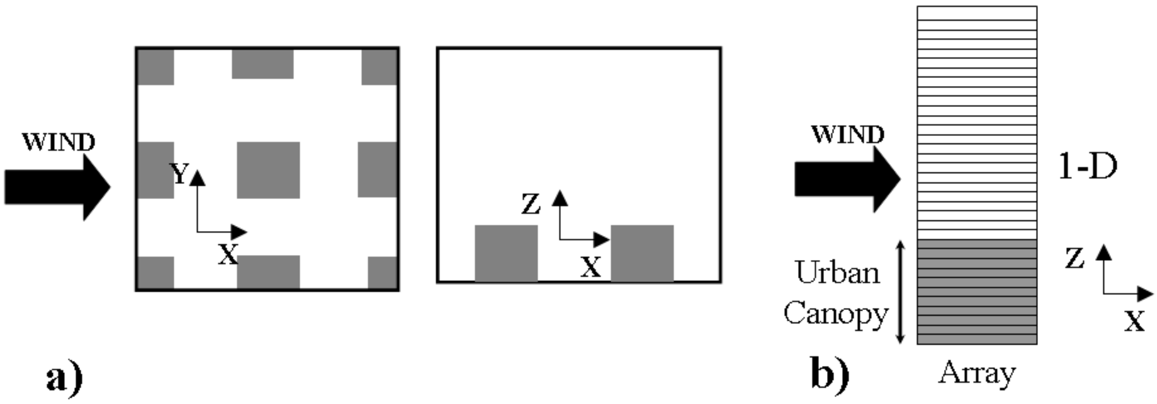

Figure 1. Scheme of domain corresponding to: a) CFD simulations, b) UCP simulations.

DESCRIPTION OF THE FLOW. COMPARISON DNS VS RANS.

DNS simulations of airflow over a periodic array of aligned cubes with wind directions of 0º, 14º, 26.6º have been performed. Results show that the flow patterns are strongly influenced by the wind direction (not shown here). To better analyse the evolution of flow patterns with wind direction it is necessary to simulate more cases with other wind directions. Due to CPU time required by DNS, RANS simulations, which can be conducted at a fraction of DNS computational time, were used. However, firstly, RANS simulations have been compared with DNS results for validation. Figures 2 and 3 show 26.6º vector maps at different heights produced by DNS and RANS models.

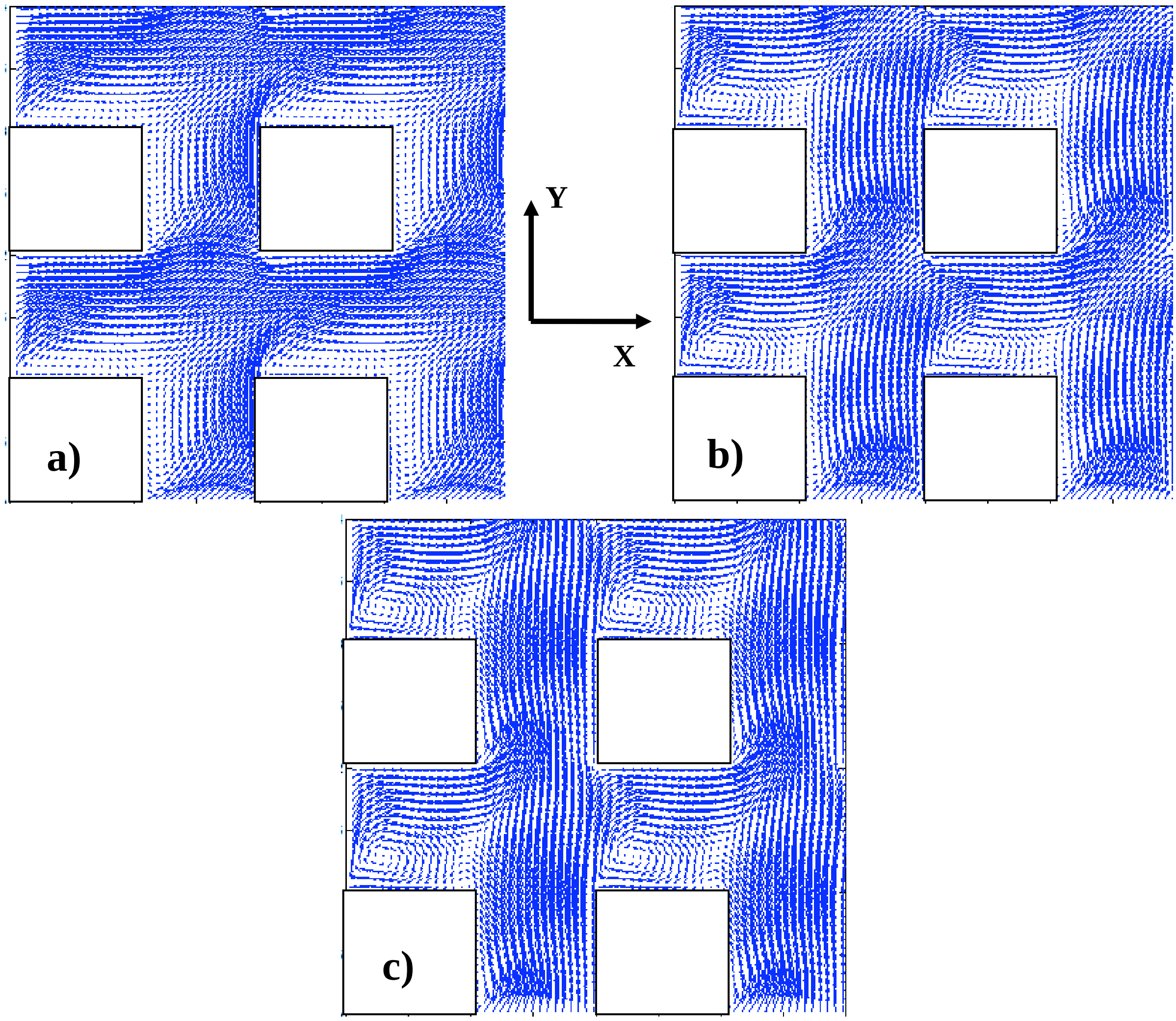

Figure 2. The wind vector fields for DNS 26.6º case at a) z/h = 0.75, b) z/h = 0.5, c) z/h=0.25.

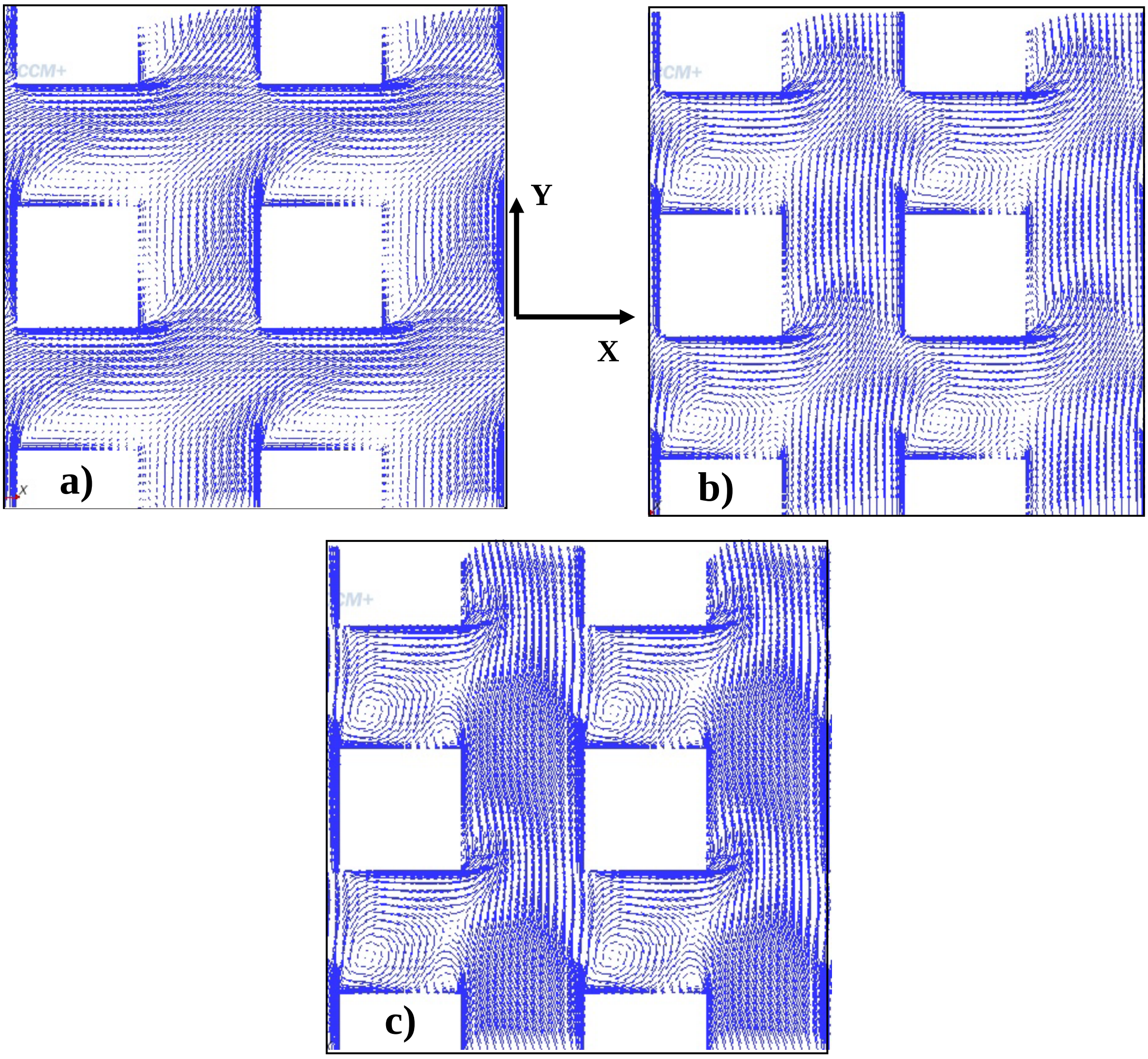

Figure 3. The wind vector fields for RANS 26.6º case at a) z/h = 0.75, b) z/h = 0.5, c) z/h=0.25.

Qualitatively RANS and DNS flow fields are similar. For 26.6º a horizontal vortex appears in the Y-direction street and increases as z decreases creating a channelled flow in Y direction at the bottom part. The flow tends to rotate (in average) towards Y direction. Note that the flow pattern obtained in periodic domains corresponds to the flow pattern in the centre of an infinite array and it is different to the flow pattern in the first streets of the array. Since RANS and DNS flow fields are similar for 0º, 14º (not shown here) and 26.6º, RANS simulations for more wind directions (0º, 7º, 14º, 26.6º, 30º, 35º, 40º, 45º) are used to study the change of flow characteristic with wind direction.

SPATIAL AVERAGE FLOW PROPERTIES AND PARAMETERIZATION OF DRAG FORCES

Since the main objective is to improve UCP, the study is focused on spatially averaged mean flow properties. Horizontally-averaged time-mean variables are studied and a comparison between RANS and DNS is made for 14º and 26.6º cases. Figure 4 show the vertical profiles of horizontally-averaged mean velocity components. In the cases with inlet wind not orthogonal to the cubes, effects of channelling in the streets in preferential directions and changes of mean wind direction with height within the canopy are observed.

The main challenge of this work is to catch the wind angle changes with height inside the canopy using a UCP. To make this we focus on drag parameterization. We used the same length scales computed in Santiago, J.L. and A. Martilli (2010). Usually the drag is parameterised as,

$$F_R = \alpha C_d U_{total}^2 \qquad (1)$$

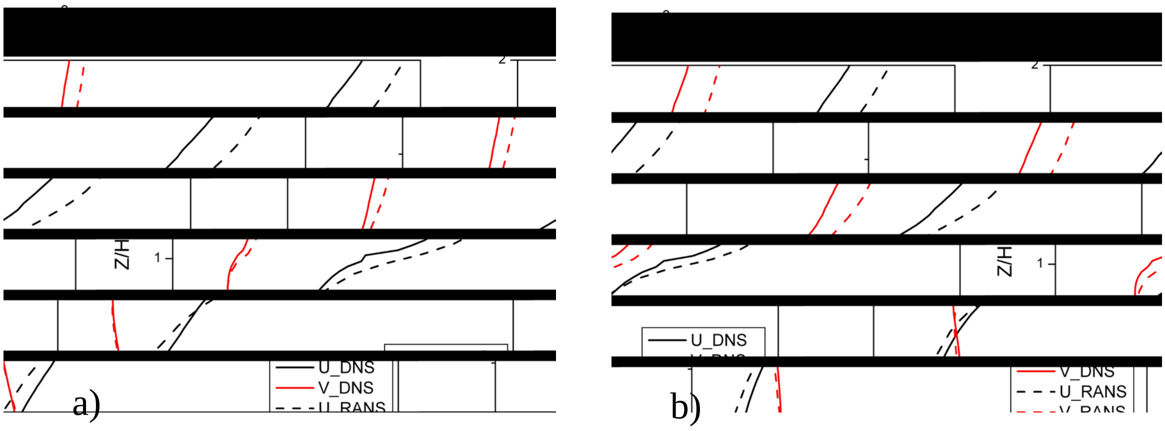

Figure 4. Vertical profiles of horizontally-averaged mean velocity components. a) 14º, b) 26º.

With the force directed against the wind. But from the results of CFD simulations it is observed that

Drag Force Angle(z) ≠ Wind angle(z) ≠ Angle $U^2/V^2(z)$

This means that a dependency of C_d with z should be introduced. However some test using drag coefficients constant with heights in order to quantify the error of the assumption of a CD constant with height are also done. Hereafter, the study is focused on the UCP developed by Martilli, A. et al. (2002) which is implemented in the meteorological model WRF and we intend to update it by using the results of this work. This UCP parameterise the drag in the momentum equations as:

$$Drag(z) = \rho S(z) C_d \left|U^{ORT}\right| U^{ORT} \tag{2}$$

The UCP takes different orientations of the streets and compute the drag over the different surfaces. For one orientation is computed over East & West faces of the cubes and in the other orientation over North & South. For simplicity, hereafter we consider the cubes aligned with NS and WE axis.

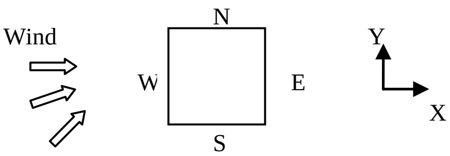

Figure 5. Scheme of UCP drag computation.

Using equation (2) or other similar we will NOT be able to obtain the correct changes in wind direction inside canopy because the drag angle is different than the wind speed angle and this relationship is not the same at each height.

Proposal of modification

The wind vector above the canopy is decomposed in two components following the directions orthogonal to the surfaces. When the orthogonal component of the velocity respect to a surface is greater than the other we compute the drag over this surface as $Drag(z)^{ORT}$ and the variables referring to this surface are called ORT. In the other case, the drag over this surface is computed as $Drag(z)^{PAR}$ and the variables are called PAR. This distinction is made because CFD results show different effects on the wind depending on this. E.g. spatially-averaged mean wind speed profiles or drag coefficient profiles (not shown here) have different shape and values for X and Y component.

In these cases the obstacles are cubes, but when the obstacles have one dimension longer than the other the assumption above should be revised.

$$\begin{aligned}\vec{D}rag(z) = \vec{D}rag(z)^{ORT} + \vec{D}rag(z)^{PAR} &= \rho S^{ORT}(z) C_d^{ORT}(z) \left|U^{ORT}\right| \vec{U}^{ORT} \\ &+ \rho S^{PAR}(z) C_d^{PAR}(z) \left|U^{PAR}\right| \vec{U}^{PAR}\end{aligned} \tag{3}$$

Note that U^{PAR} is orthogonal to the surfaces PAR.

Some problems arise to parameterise the drag coefficients. Two coefficients with a dependency with the inlet wind angle and height should be parameterised. In these cases (non-orthogonal wind) it seems that this dependency cannot be neglected. In the cases with incident wind orthogonal to the cubes albeit is possible to parameterize the drag coefficient as constant with height, however if the same is done for incident wind not orthogonal to the faces of the cube, it will not be possible to catch the mean wind rotation inside the canopy. Some tests using 1D-version of the UCP (similar to UCP simulations in Santiago, J.L. and A. Martilli, 2010) are made. On one hand, a test using the Cd profiles computed from RANS simulations are run.

And on the other hand, tests using some parameterizations of drag coefficients constant with height are simulated. The details are described as follow:

Test 1:

$C_d^{ORT}(z, angle)$ and $C_d^{PAR}(z, angle)$ are computed directly from RANS simulations. These profiles are used in UCP.

Test 2:

We compute $C_{deq}^{ORT}(angle)$ and $C_{deq}^{PAR}(angle)$ in a similar way of the C_{deq} in Santiago, J.L. and A. Martilli (2010). With this approximation, we remove the z dependency but keeping the drag force integrated in the whole urban canopy equal to that computed by the RANS simulations.

Test 3:

We take the same value of Cd for the two orientations and parameterise the force as

$$F_R(z, angle) = \alpha C_{dtoteq}(angle)\ U_{total}^2(z, angle) \quad (4)$$

Here the force is directed against the mean wind.

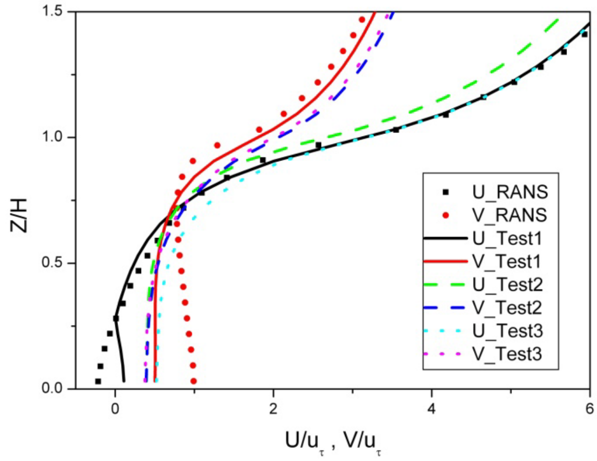

Figure 6. Vertical profiles of horizontally-averaged mean velocity components obtained by RANS in comparison with profiles of velocity components from UCP with different drag parameterisations for the case of 26º

For 26º, U is well predicted by test 1. Inside the canopy, it is overestimated by the other C_d parameterizations. Above the canopy, it is well predicted except for test 2 that slightly underestimates U values. V inside the canopy is underestimated by every parameterization. Above the canopy, a slight overestimation is observed for test 2 and test 3. Similar results are obtained for other angles. The main problem found when drag coefficients are parameterised (removing z dependency) is that UCP with these coefficients does not reproduce the wind direction inside canopy. In general, close to ground U is overestimated, especially for small angles where Cd at this height is very high. And U is always greater than V inside the canopy producing a wrong wind direction. These results show that, at least for these cases, it is necessary to take into account the height-dependency of the drag coefficient. A constant with height drag coefficient cannot catch the wind direction inside the canopy. This may be important for air quality applications, since it will affect the direction of the pollutant dispersion.

CONCLUSIONS

The results show that:

1) The flow within the array, when the inlet wind is not orthogonal to the buildings, is very complex and sometimes unintuitive (including effects such as channelling in the streets in preferential directions and changes of mean wind direction with height within the canopy)
2) The importance of a good parameterization of drag to reproduce the effects mentioned above. In particular, a height-dependent drag coefficient seems to be necessary.
3) UCP reproduces spatially-averaged flow similar to those computed from CFD when a suitable parameterisation of drag forces is used.
4) Future studies are necessary to improve the drag parameterisation and to generalise it to other layouts.

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