Micrometeorological modelling in urban areas

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ABSTRACT:
Micrometeorological studies in urban zones are more complex than in rural zones. Inside urban canopy, 3-D flow structures are created by the urban geometry (streets with different configurations of buildings). In this paper, the application of microscale models (CFD models) to urban micrometeorology is studied and a CFD model is applied to an array of cubes representing a portion of a city. The model results are validated against wind tunnel measurements made with the same geometry and are analysed to understand the flow properties in this case. Strong horizontal inhomogeneities of the mean and turbulence variables are found inside the canyons showing that the representativeness of measurement in one point is limited spatially. In addition, the CFD results are spatially averaged over thin slices encompassing a cube-canyon unit in the central zone of the array showing the special importance of average properties as the dispersive stress inside the urban canopy created by the cubes.
Key words: Micrometeorology, urban areas, CFD models, RANS, *k-ε* turbulence model, validation, average properties, urban parameterization, array of cubes.

Modelización Micrometeorológica en Áreas Urbanas

RESUMEN:
Los estudios de micrometeorología en zonas urbanas son más complejos que en zonas rurales. Dentro de la *canopy* urbana, se crean estructuras de flujo de aire tridimensionales debido a la propia geometría urbana (calles con diferentes configuraciones de edificios). En este artículo, se estudia la aplicación de modelos a microescala (modelos CFD) a la micrometeorología urbana, para ello se aplica un modelo CFD a una matriz de cubos que representa una porción de ciudad. Los resultados del modelo se validan frente a medidas en túnel de viento realizadas con la misma geometría, y una vez validados se analizan para comprender las propiedades del flujo en este caso. Se encontraron fuertes inhomogeneidades horizontales de las variables medias y turbulentas dentro de los cañones de la calle, mostrando que la representatividad de las medidas en un punto está limitada espacialmente. Además, los resultados del modelo CFD son promediados espacialmente sobre láminas delgadas horizontales que rodean una unidad cubo-cañón en la zona central de la matriz, mostrando la especial importancia de las propiedades espacialmente promediadas como el *dispersive stress* dentro de la *canopy* urbana creada por los cubos.
Palabras clave: Micrometeorología, áreas urbanas, modelos CFD, RANS, modelo de turbulencia *k-ε*, validación, propiedades promedio, parametrización urbana, matriz de cubos.

1. INTRODUCTION

Micrometerological studies in urban areas have been motivated, mainly, by the interest in air pollutant dispersion and local climatology (Urban Heat Island phenomena). First studies date back to the seventies and focus on the differences between the rural and urban values for temperature and heat fluxes (Nunez & Oke, 1977), or wind (Johnson & Bornstein 1974). It was clear, since then, that micrometeorology in urban areas is very different than in rural areas. This was confirmed later, and more deeply investigated, by Rotach (1993a, 1993b). He measured turbulent variables at different heights within and over a street canyon in Zurich (Switzerland), finding that turbulent fluxes are not constant with height in the lower part of the Surface Layer, called Urban Roughness Sublayer (URS, 1-3 times the mean building height). Since the invariance with height of the turbulent fluxes is a necessary condition for the Monin Obukhov Similarity Theory (MOST), main consequence is that the formulas derived from MOST, valid over homogeneous rural areas, cannot be applied in urban areas. This was a problem, because mesoscale meteorological models, as well as dispersion models (both Eulerian and Lagrangian), usually adapted MOST formulas to urban areas by only changing the roughness length. Since the Urban Roughness Sublayer is a very sensitive region, where people live and emissions are located, it is important to better understand the micrometeorological behaviour in urban areas, in order to improve the estimation of pollutant dispersion and local climatology.

Mesoscale models at high resolution (~1 km) can not solve the buildings located in urban regions and their effects on local meteorology must be parameterized. Thus, CFD (Computational Fluid Dynamics) models that solve building explicitly are used to investigate micrometeorology inside the Urban Roughness Sublayer. On the other hand, the typical CFD numerical domains, for computational reasons can not be large enough to represent the whole city and mesoscale models at high resolution are necessary to study the urban impact at local scale.

Aim of this paper is to show how CFD building resolving models can be used to improve the understanding of microclimatology in urban areas and test urban parameterizations for mesoscale models.

In the following sections the main reasons behind the complexity of the urban microclimatology are outlined (section 2). In section 3 a CFD model is described, and in section 4 an example of application to a regular array of cubes is presented together with a validation in section 5. Flow features are investigated in section 6 and averaged variables, useful for mesoscale models, are analysed in section 7. Conclusions are in section 8.

2. MICROMETEOROLOGY IN CITIES. WHY CITIES ARE COMPLEX?

A city is composed of buildings of variable size, arrayed in blocks and intersected by streets. Such complex surfaces strongly affect the urban boundary layer structure. The two most important factors are:

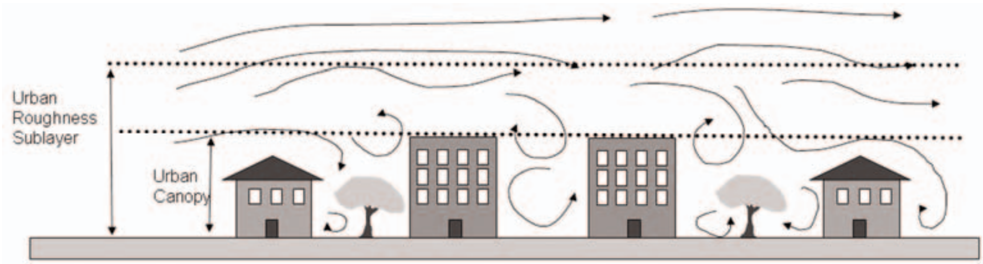


Figure 1.- Representation of the urban canopy and the Urban Roughness Sublayer.

— Mechanical. Buildings induce a sink of momentum (drag), and increase the transfer of energy from large to small eddies.

— Thermal. Buildings induce differential heating (cooling) of sunlit (shaded) surfaces, radiation trapping in street canyons, and a reduction in latent heat fluxes, which affect the sensible heat flux to the atmosphere.

The atmospheric features generated by such heterogeneities have a spatial scale of the order of few meters (the size of buildings or streets), and are strongly variable in the three directions. The structure of the URS is, then, the result of the combination of such features (Fig. 1). This horizontal variability of the flow makes impossible many of the assumptions usually adopted in Surface Layer Theory over flat and homogeneous surfaces (typically horizontal derivatives cannot be neglected in the equations). The consequences are that basic Navier Stokes and turbulence equations cannot be simplified enough to be solved analytically, and the representativeness of a point measurement is spatially limited. A complete analysis of the flow and turbulence in urban areas must, then, account for the three-dimensionality of the flow. Since in many real urban cases it is impossible to set up a measurement network dense enough to capture the relevant atmospheric features, the analysis can be carried out by solving numerically the Navier-Stokes equations (with a CFD model) at a resolution high enough to explicitly resolve the buildings and the relevant atmospheric features. In this case, the degree of confidence in model results depends on the validation against point measurements (full scale or wind tunnel).

In the following some of the results presented in depth in Santiago et al. (2007), and Martilli & Santiago (2007) are used to illustrate this technique.

3. MICROSCALE MODELS (CFD)

CFD models are used for a wide range of purposes such as turbomachinery, automotive, aerodynamics, etc. In the last years, the use of CFD for micrometeorological applications has increased. These models can solve explicitly obstacles like building and their resolution can reach values minor than 1 m. However, their numerical domain can not be very large, due to computational reasons, and usually only a small portion or district of a city is simulated.

CFD models are based on the fluid dynamic equations (mass, momentum and energy conservation). These models are classified in different types depending on the way the equations are solved and especially on the way the turbulence is represented. Direct Numerical Simulations (DNS) models integrate numerically the equations without any tuning or modelling assumption (Coceal et al. 2006). All scales of motions are explicitly resolved. For high Reynolds numbers, this implies a very high resolution. For this reason, their application to urban micrometeorology is very difficult with the current computer resources. Large Eddy Simulations (LES), another important type of CFD models, are based on a spatial filtering of fluid dynamic equations. The large eddies are resolved, while the small eddies are filtered and their effect is parameterized. In LES models, the spatially filtered, time-dependent equations are solved for a time large enough to allow the computation of a statistic. LES models are less CPU expensive than DNS models and they are increasingly used to simulate flows over complex geometries (Xie & Castro 2006), but they are still too CPU expensive to be extensively used in micrometeorological studies over urban areas. The third type is the Reynolds Averaged Navier-Stokes (RANS) models that perform an ensemble average of the equations. With these models, only the deterministic features are explicitly resolved, while the turbulent features are filtered out, and their effect is parameterized. Nowadays, evaluating the fitting with experiments and CPU time required, they are the more suitable. LES and DNS results would predict with higher accuracy the wind flow, since less features are parameterized, but they need a much higher computational load (about two orders of magnitude in CPU time for LES versus RANS). In the application to atmospheric flows, there are uncertainties in initial and boundary conditions. The atmospheric conditions are not known in detail for real situations and these uncertainties could be comparable to the difference between LES and RANS results. As explained, RANS models are based on the ensemble average of the fluid dynamic equations and a turbulence closure is necessary. For micrometeorological applications, the standard k-ε closure is usually used (Sini et al. 1996; Santiago et al. 2007). Therefore, the governing equations are the continuity equation in incompressible form (1), the Navier-Stokes equations (2) and one equation for the turbulent kinetic energy, k, (3) and another for the dissipation rate of turbulent kinetic energy, ε, (4).

$$\frac{\partial u_j}{\partial x_j} = 0 \tag{1}$$

$$u_j \frac{\partial u_i}{\partial x_j} = - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\mu}{\rho} \frac{\partial^2 u_i}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j} (\overline{u'_i u'_j}) + g_i \tag{2}$$

$$u_j \frac{\partial k}{\partial x_j} = \frac{1}{\rho} \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + \frac{G_k}{\rho} - \varepsilon \tag{3}$$

$$u_j \frac{\partial \varepsilon}{\partial x_j} = \frac{1}{\rho} \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{1}{\rho} C_{\varepsilon 1} G_k - \frac{\varepsilon}{k} C_{\varepsilon 2} - \frac{\varepsilon^2}{k} \tag{4}$$

where, μ is the dynamic viscosity; g_i is the gravitational body force $(g_i = -g\delta_{i3})$; $-\overline{u_i' u_j'}$ is the Reynolds stress that is computed by relating Reynolds stresses to the mean velocity gradients, namely:

$$-\overline{u_i' u_j'} = \frac{1}{\rho} \mu t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} k \delta_{ij} \tag{5}$$

μ_t is the turbulent eddy viscosity expressed as $\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$; G_k is the turbulent kinetic energy production; σ_k $(= 1.0)$ and σ_ε $(= 1.3)$ are model constants that connect the diffusivities of k and ε to the turbulent eddy viscosity μ_t; C_μ, $C_{\varepsilon 1}$ and $C_{\varepsilon 2}$ are model constants equal to 0.09, 1.44 and 1.92 respectively. These constant values are often used for a wide range of turbulent flows (Launder and Spalding, 1974).

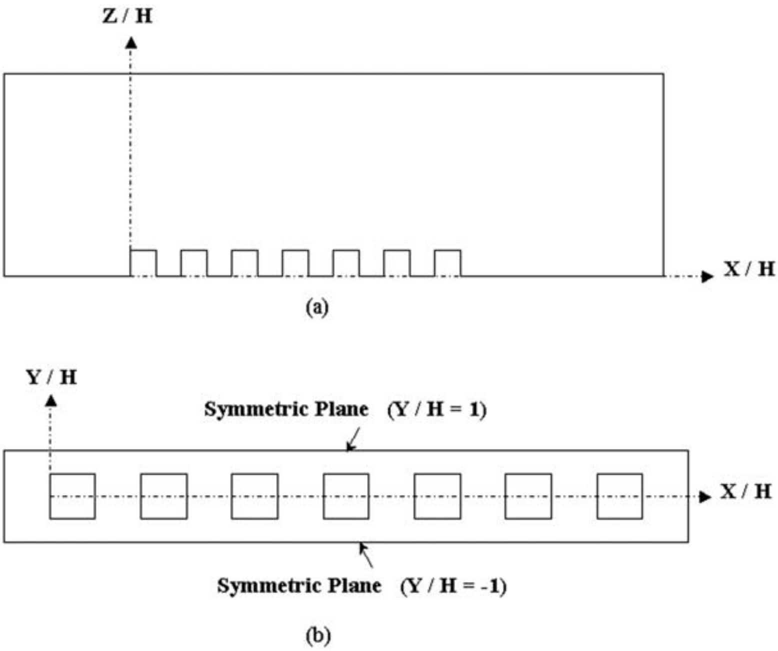


Figure 2.- Numerical domain used. (a) lateral view and (b) top view.

4. DESCRIPTION OF THE CASE ANALYSED

In this study, a portion of a city is simulated by means of a regular array of cubes representing buildings. The cube edge length is equal to the face-to-face spacing in the streamwise and spanwise direction. The configuration of wind tunnel experiment is formed by 7 cubes in the streamwise direction and 11 cubes in the spanwise direction; in addition the wind flow is also perpendicular to the array and a reference velocity of $u_{ref} = 3$ m s^{-1} (equal to the upstream velocity at $Z = H$) is used.

The mean wind direction at the inflow is perpendicular to the array. For the numerical simulations, a row of buildings with symmetric conditions at lateral planes is used, representing an infinitive array of cubes in the spanwise direction (Fig. 2). In order to compare the numerical results against wind tunnel measurements, the same cube edge length ($H = 0.15$ m) and the same inflow (velocity and turbulent kinetic energy) used in the wind tunnel have been used. The boundaries of the numerical domain are located far from the array in order to minimize their impact on the solution. The top of the numerical domain is placed at $Z/H = 8$, the inflow boundary at $Z/H = 5$ from the first cube and the outflow boundary at $Z/H = 15$ from the last cube. Concerning the numerical mesh, a grid of 202 x 44 x 40 with 12 grid points per cube in the X and Z direction close to the building is used. In length units, the grid size near the buildings is $\Delta X = 0.0125$ m, $\Delta Z = 0.0125$ m, $\Delta Y = 0.0068$ m. The grid size increases in both directions farther away from the array. In addition, a grid independence test was also carried out using a finer grid (303 x 60 x 60 grid points). The differences between the results (U, W, k) computed using the two grids are very small. Therefore, the independence of flow solution on grid resolution is fulfilled. The numerical simulation is made by FLUENT CFD using RANS equations with standard k-ε, described in the previous section.

5. VALIDATION

The numerical results of this case are validated against wind tunnel measurements (Brown et al. 2001). To ensure the quality of microscale meteorological model results, a procedure of validation is needed. In this case, the "hit rate" test (Schlünzen et al. 2004) is applied as statistical parameter. This is based on the calculation of a hit rate (q) for each variable. Following Schlünzen et al. (2004), a value of $q > 66\%$ for comparison with wind tunnel data is considered acceptable for the model validation. Thus, this is a simple way to evaluate the differences between model results and experimental data. q is computed as,

$$q = \frac{N}{n} = \frac{1}{n}\sum_{i=1}^{n} N_i \quad \text{with} \quad N_i = \begin{cases} 1 \text{ if} \left|\frac{P_i - O_i}{O_i}\right| \leq RD \text{ or } \left|P_i - O_i\right| \leq AD \\ 0 \quad \text{elsewhere} \end{cases} \qquad (6),$$

where n is the total number of points compared, O_i and P_i are wind tunnel data and model results, respectively. RD and AD represent a relative deviation and an absolute deviation of model results from experimental data, respectively. The hit rate test with a relative deviation of $RD = 0.25$ for all variables and an absolute deviation of $AD = 0.15$ m s^{-1} for U and W and $AD = 0.15$ m^2 s^{-2} for k, gives values over 66% for all variables ($q(U) = 95\%$; $q(W) = 77\%$; $q(k) = 81\%$).

The hit rate test provides information about the global agreement. To investigate more deeply the agreement in the zones of more interest (e. g. within the canopy), vertical profiles are analysed where measurements are available. We are interested in analyse the wind flow and turbulence features inside the urban canopy, then our validation focus on the mean streamwise velocity (U), the mean vertical velocity (W) and the turbulent kinetic energy (k). Vertical profiles are analysed for the fourth cube-canyon unit, chosen as representative

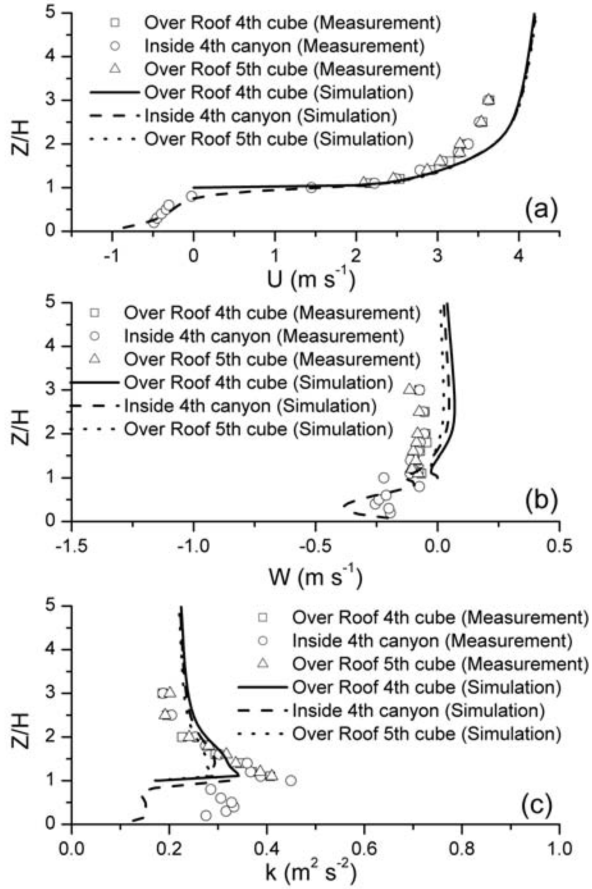


Figure 3.- Vertical profiles at 3 different X locations at plane *Y/H = 0*. *X* locations: *X/H = 6.5* (over the roof of the fourth cube), 7.5 (inside the fourth street canyon) and 8.5 (over the roof of the fifth cube). (a) Mean streamwise velocity *(U)*. (b) Mean vertical velocity *(W)*. (c) Turbulent kinetic energy *(k)*.

of a central canyon in a city (Santiago et al. 2007). The vertical profiles inside this canyon and on top of the near cubes are shown in Fig. 3. For *U* the agreement is very good inside the canopy. Above the canopy the model has a tendency to overestimate the wind intensity. The reason of this behaviour is not clear, but it has been observed also in other numerical studies (Xie and Castro, 2006). However, for *W*, an overprediction of its intensity within the canopy is detected and for *k* an underprediction is found. In conclusion, the model seems to have a global acceptable behaviour (the hit rate test is passed) reproducing the main features of wind flow structures, but it has some problems with the magnitude of vertical velocity and turbulent kinetic energy within the canopy. More details concerning the validation procedure can be found in Santiago et al. (2007).

6. DESCRIPTION OF MICROMETEOROLOGICAL FEATURES

The analysis of the vertical section (XZ plane) in the centre of the fourth canyon unit (Fig. 4), and the horizontal sections for the same unit at Z/H=0.5 and Z/H=1 (Figs. 5 with vertical velocity and Figs. 6 with turbulent kinetic energy contours) clearly show the presence of a vortex in the vertical plane in the centre of the canyon, and two vortex in the horizontal plane at mid-height. This flow structure generates strong horizontal variations of mean vertical velocities being very important, for example, for the dispersion of the pollutants emitted at street level. Moreover, the turbulent kinetic energy fields also show strong horizontal variations (Fig. 6).

As mentioned, the flow behaviour is very different in comparison with flow over flat and homogeneous rural zones, where the horizontal gradients of the mean variables are usually very small. In urban areas the value of one variable at one point

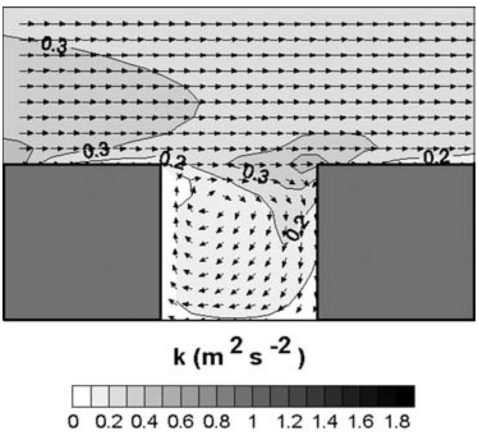
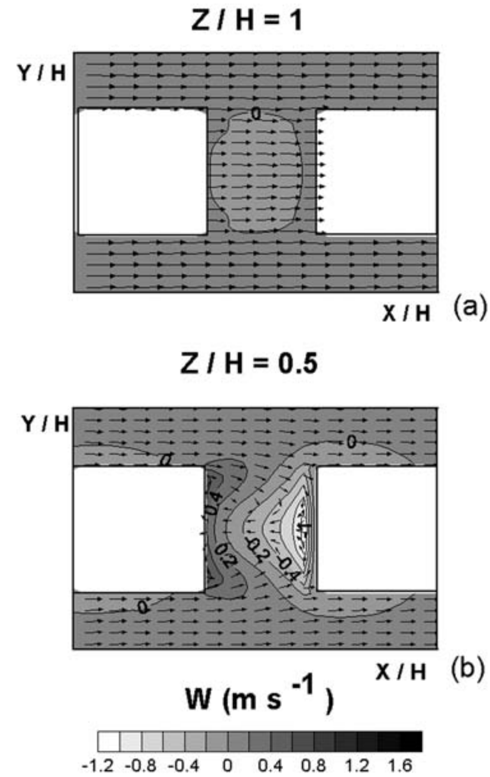


Figure 4.- Flow field and turbulent kinetic energy contours at *XZ* plane *Y/H = 0* focused on the fourth canyon.



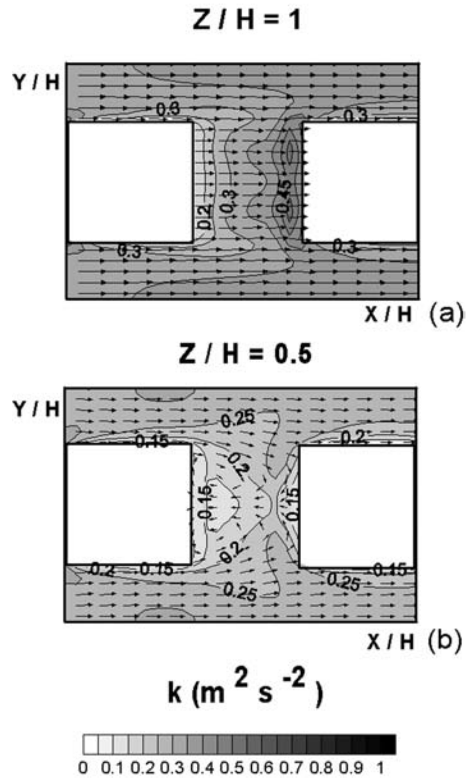


Figure 5.- Wind field and mean vertical velocity *(W)* contours in the fourth canyon at horizontal planes (a) *Z/H = 1* and (b) *Z/H = 0.5*.

Figure 6.- Wind field and turbulent kinetic energy *(k)* contours in the fourth canyon at horizontal planes (a) *Z/H = 1* and (b) *Z/H = 0.5*.

inside the street is not representative of the behaviour of this variable in the whole street. Thus, to characterise the flow inside a street, it is necessary to investigate the three dimensional features that develops within the canopy.

7. AVERAGE PROPERTIES

In some applications (e. g. non-building resolving atmospheric models as mesoscale models that have a typical spatial resolution of several hundreds to few kilometres in the horizontal, see Martilli et al. 2002), or in theoretical studies where a one dimensional framework is needed (Belcher et al. 2003), it is necessary to perform a spatial average of the Reynolds Averaged Navier-Stokes equations. For a spatially heterogeneous flow, as the one in urban canopies, this double averaging (time or ensemble, here considered as equivalent, and space) has some consequences, among the most important the appearance of the dispersive fluxes. Formally, let indicate the time average over a time larger than the characteristic turbulent time scale ΔT for a generic variable φ with an overbar $\bar{\varphi} = \frac{1}{\Delta T} \int_{T-\Delta T/2}^{T+\Delta T/2} \varphi dt$ (this average can also be seen as an ensemble average), and the space average (over a volume large enough to smooth out the horizontal heterogeneity) with brackets $<\varphi> = \frac{1}{V} \int_V \varphi dv$. The departures from the averages are, respectively, $\varphi' = \varphi - \bar{\varphi}$, $\tilde{\varphi} = \bar{\varphi} - <\bar{\varphi}>$. As a consequence a variable can be split in three parts $\varphi = <\bar{\varphi}> + \tilde{\varphi} + \varphi'$. Here represents the stochastic, time variant turbulent component, while $\tilde{\varphi}$ represents the time averaged structured smaller than the volume over which the average is performed, and $<\bar{\varphi}>$ are the time averaged structure larger than the volume over which the average is performed. For the time and space averaged fluxes (vertical, for example), the development leads to:

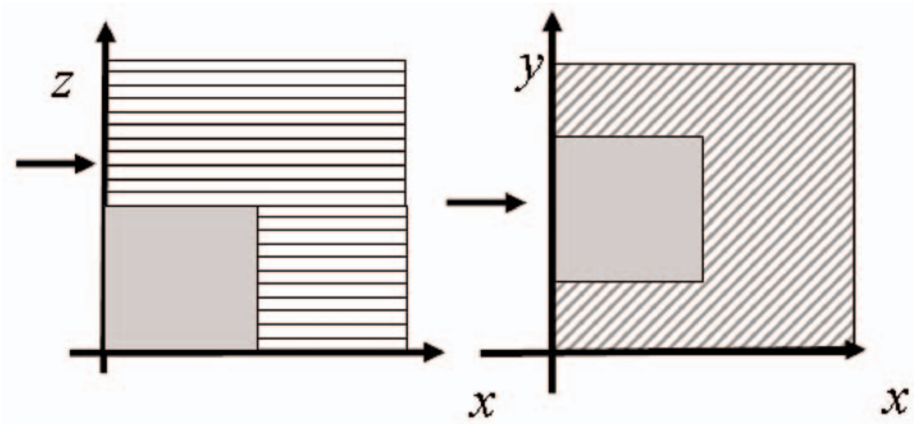
$$<\overline{\varphi w}> = <\bar{\varphi}> <\bar{w}> + <\overline{\varphi' w'}> + <\tilde{\varphi}\tilde{w}> \quad (7)$$

where the first term on the right hand side is the resolved flux, the second is the space average of the turbulent flux, and the third is the dispersive flux generated by the time averaged structures smaller than the volume over which the average is performed. A more detailed analysis is described by Martilli & Santiago (2007).

Using the results presented in the previous section, let investigate the relative importance of these three fluxes. Here the averages are performed over thin slices encompassing a 'canyon unit' (see Fig. 7a). For the 4^{th} canyon (Fig. 7b), it is possible to see that the dispersive stress is a significant part of the total flux in the central part of the canopy, and, for this specific case, it has opposite sign than the Reynolds Stress (e. g. it is countergradient, since the average velocity monotonically increases with height). This is a relevant result, since the dispersive stress is in general neglected in many applications (Martilli & Santiago, 2007).

8. CONCLUSIONS

In this article a methodology to study micrometeorology in urban areas has been presented. The starting point is the recognition that the meteorological features in the Urban Roughness Sublayer (URS, the lower part of the Surface Layer, with a depth of 1-3 times the mean building height) are three dimensional and strongly affected by the individual buildings. The consequence is that the representativeness of spatial measurements is limited. To gain a three-dimensional picture of the flow and turbulent fields, it is proposed to use a CFD model with a k-ε turbulence closure (RANS). The quality of model results is tested against wind tunnel measurements over an array of cubes. This comparison shows that the CFD model fulfil the quality criteria proposed by Schlünzen et al. (2004), and it is able to reproduce, at least qualitatively, the a)



b)

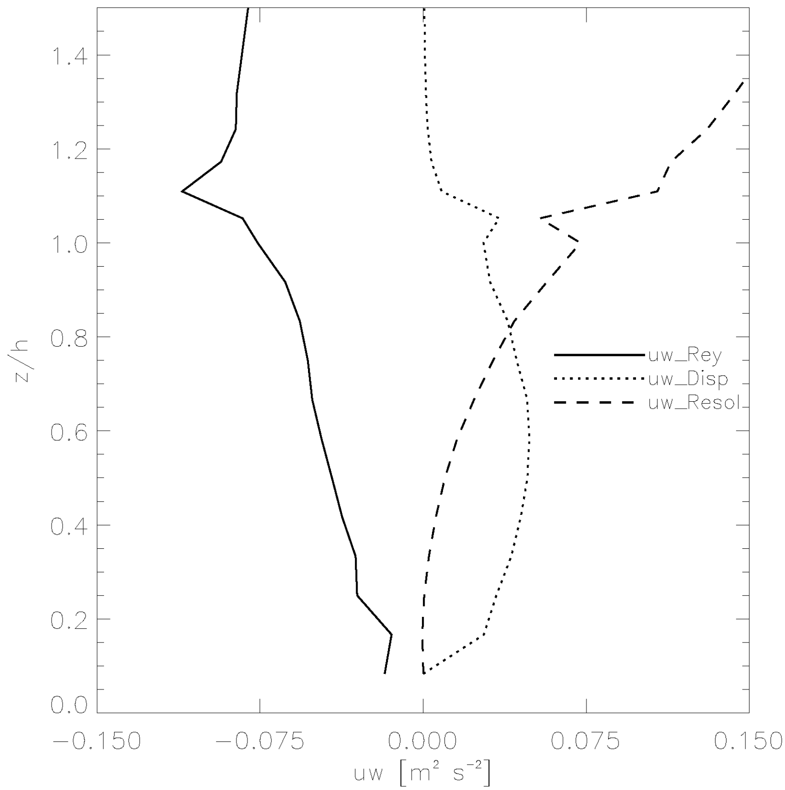


Figure 7.- a) averaging areas for the 4th canyon unit. b) vertical profiles of mean momentum transport (dashed line, *uw_Resolv* = $<\bar{u}><\bar{w}>$), spatially averaged Reynolds stress (solid line, *uw_Rey* = $<\overline{u'w'}>$), and dispersive stress (dotted line, *uw_Disp* = $<\tilde{u}\tilde{w}>$).

general structure of the flow. The analysis of the flow and the turbulent field carried out with the model results, confirms the strong horizontal variability of mean and turbulent variables.

Finally an analysis of spatially averaged variables is performed since in many applications and theoretical works a one dimensional framework is needed. This analysis highlights the importance of the dispersive stress in urban areas.

9. ACKNOWLEDGEMENTS

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