J5.2 AVERAGE FLOW PROPERTIES USEFUL FOR URBAN PARAMTERIZATIONS DEDUCED FROM CFD SIMULATIONS OVER A REGULAR ARRAY OF CUBES.

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1. INTRODUCTION

When a numerical atmospheric model is run over a city without a spatial resolution high enough to resolve every building, the problem of how to represent the impact of the buildings contained within a grid cell on the spatially averaged variables arises. This is the common case for mesoscale models, for example, that are often used to provide meteorological fields to air quality models. In recent years several parameterisations have been proposed to answer this problem (Brown and Williams, 1998, Martilli et al. 2002, Coceal and Belcher, 2004, etc.). Although such schemes show an improvement of the general behaviour of the flow at the mesoscale, their validation have been particularly difficult, because of the lack of spatially averaged variables. In fact, these are the proper fields that can be compared to the results of a mesoscale model.

In this paper, we use results from a CFD numerical model run over an array of cubes and validated against wind tunnel data (see full details in the Santiago et al. paper presented in this session), to derive such spatial average values. The advantage of the CFD results, in fact, is that provides a very dense (in space) set of data, which makes meaningful to derive spatial average values (things that it is rarely possible from real scale measurements).

2. AVERAGING TECHNIQUE

For a flow with strong spatial inhomogeneities as the flow over an array of cubes, it is important to split between time and space averages. Using overbars to indicate time average and brackets to indicate space average, we have for a generic variable y

$$y'(\vec{x},t) = y(\vec{x},t) - \overline{y}(\vec{x})$$
$$\tilde{y}(\vec{x}) = \overline{y}(\vec{x}) - <\overline{y}>$$
$$y(\vec{x},t) = y'(\vec{x},t) + \tilde{y}(\vec{x}) + <\overline{y}>$$

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and for the (co-)variances

$$<\overline{fy}> = <\overline{f}><\overline{y}> + <\overline{f'y'}> + <\tilde{f}\tilde{y}>$$

Here the first term on RHS is the mean (co-) variance, the second is the 'traditional' turbulent term, and the last term is the so-called dispersive (co-)variance, arising from the spatial average of the product of the spatial fluctuation of the time-averaged values.

Note that the CFD model provides a steady state solution. However, what is steady state are the time-averaged variables (where the average is done over a time larger than the turbulent time scale) $\overline{y}(\vec{x})$. So, for every grid point the CFD provides stationary time averaged values of the three components of the wind and the pressure, and, also, time averaged turbulent variances and co-variances $\overline{y'f'}(\vec{x})$.

Seven spatial averages are then performed: one for every building canyon unit (see Fig. 1), and one for the whole array of buildings. In the vertical the resolution of the CFD model is used (this is consistent with the fact that in mesoscale modelling the resolution in the vertical is usually much finer than in the horizontal). In other words, the volumes over which the averages are performed are thin slices with the horizontal surface presented in Fig. 1, and a vertical depth equal to the resolution of the CFD model.

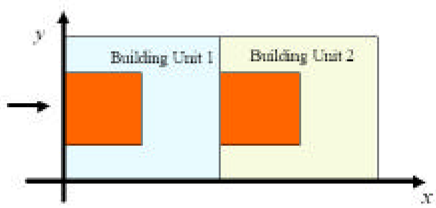

Figure 1. Horizontal section of the volumes over which the averages are performed. Orange areas are the cubes.

3. MEAN HORIZONTAL WIND

Spatially averaged horizontal wind show a quite simple behaviour (Fig. 2). Within the cube's canopy, it increases with height in a nearly linear way (only the first unit has a different behaviour). Above the canopy, the profile is logarithmic, with a displacement height equal to the cube's height.

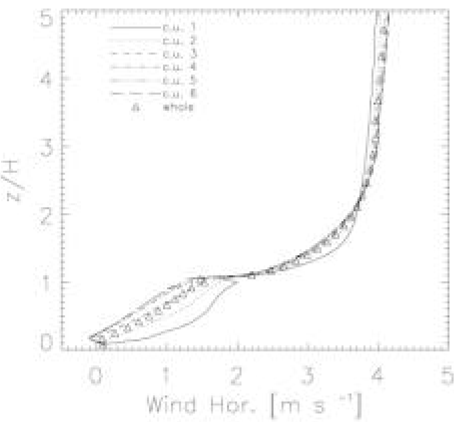

Figure 2. Vertical profiles of mean horizontal wind. ***H*** *is the height of the cubes.*

4. MOMENTUM FLUXES

The non-explicitly resolved vertical momentum fluxes are split in the turbulent component (or the spatial averaged Reynolds stress) $<\overline{u'w'}>$, and the dispersive component $<\tilde{u}\tilde{w}>$, as explained above. As shown in Fig. 3, the dispersive stress has opposite sign and comparable magnitude to the Reynolds stress. This means that (at least for this array configuration), the dispersive flux is counter gradient, and cannot be considered neglectable as it has been usually done. A more careful analysis of the results (not shown), shows that the responsible of the positive counter-gradient flux is a downward motion of slow air, linked with the vortex developing between the buildings. This means that such flux is also non-local, since it is the result of the building-scale vortex.

5. DRAG

The sink of the spatially averaged momentum induced by the buildings is the result of the pressure acting on the surfaces of the obstacle. Mathematically for the *x* component (parallel to incident wind direction) it can be represented as:

$$\frac{1}{rV}\int_{S_{obst}} Pn_x ds$$

where r is the air density, V is the air volume over which the average is performed, S_{obst} is the surface of the obstacle delimiting the volume, P is the pressure, and n_x is the x component of the unit vector normal to entering in the surface. The vertical profiles of such term (Fig. 4a) show that the largest loss of momentum happens at the first cube. The others cube have similar profiles in shape and magnitude, with an increase with height and a maximum at the top of the canopy. The traditional way to represent this term in non-obstacle resolving models is to assume that is proportional to the square of the wind speed and the obstacle density. Using the CFD results, we can estimate the numerical value of the drag coefficient, defined as:

$$C_D = \frac{\frac{1}{rV}\int_{S_{obst}} Pn_x ds}{aU|U|}$$

with α (in m^{-1}) the vertical surface building density (facing the wind). The results presented in Fig. 4b show (for canyon unit 5, but similar results can be found for the others units, except the first) that this coefficient is not constant, and decreases with height. This is because in the lower part of the canopy, wind speeds are very weak or close to zero (Fig. 2), yielding very large values of the ratio. To adopt this formulation it is necessary to use height dependent values of C_D, which is not very practical.

An alternate solution to this problem can be found if the pressures against the obstacle surfaces are considered dependent not on the mean wind speed but on the instantaneous value of the wind. We propose, then to introduce two new velocity scales based on the turbulent fluctuations of wind speed, and the coherent motions within the cell (e. g. canyon vortices). The first can be estimated from the averaged **tke** as:

$$v_{tke} = \sqrt{2tke}$$

$$tke = \frac{1}{2}\left(<\overline{u'^2}> + <\overline{v'^2}> + <\overline{w'^2}>\right)$$

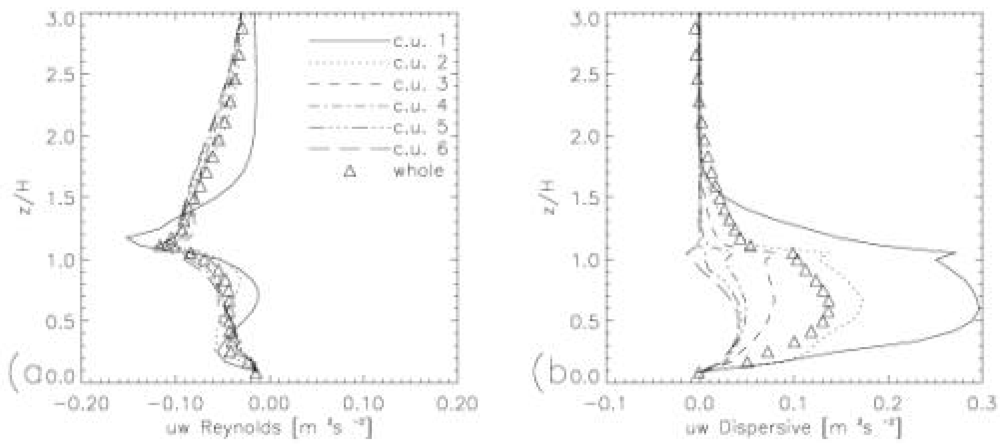

Figure 3. Vertical profiles of the spatially averaged Reynolds stress (a), and the dispersive stress (b).

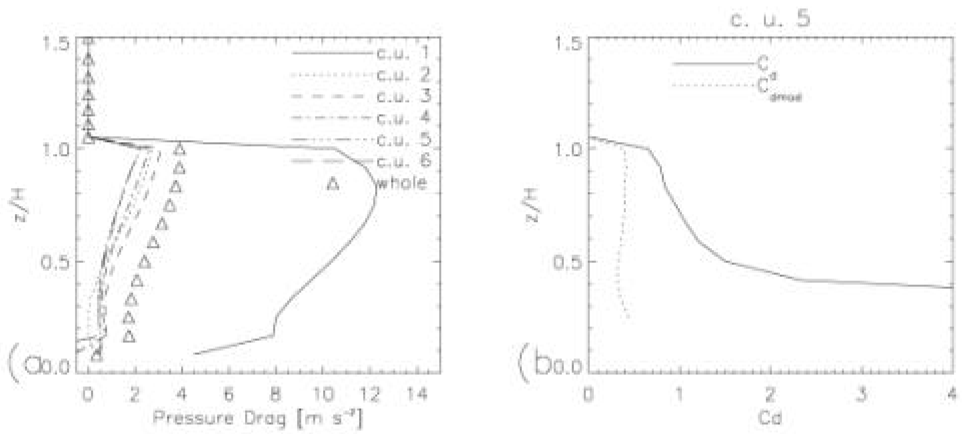

Figure 4. a) Vertical profiles of drag term. b) vertical profiles of C_d and C_{dmod} (see text) for canyon unit 5.

The second can be estimated from the dispersive variances defined above, as

$$v_{dke} = \sqrt{2dke}$$

$$dke = \frac{1}{2}\left(< \tilde{u}^2 > + < \tilde{v}^2 > + < \tilde{w}^2 >\right)$$

Where with the symbol **dke** we indicate the **dispersive kinetic energy**, or the kinetic energy due to the time averaged structures smaller than the grid cell. So, the expression for the modified ***C_{Dmod}*** can be written as:

$$C_{D\,\mathrm{mod}} = \frac{|U|}{U} \frac{1}{\left(U^2 + v_{tke}{}^2 + v_{dke}{}^2\right)} \frac{1}{rV} \int_{S_{obst}} Pn_x$$

As shown in Fig. 4b, the vertical profile of ***C_{Dmod}*** is much more regular and constant with height than the one derived from the original formulation, with values for the coefficient close to 0.4.

6. CONCLUSIONS

Main conclusions are:

- Vertical profile of the time and spatially averaged horizontal wind increases linearly within the canopy and logarithmically above.
- Dispersive momentum fluxes are counter gradient and cannot be neglected within the canopy.
- Assuming that the drag force is proportional to the sum of the square of the mean horizontal wind speed and square of two velocity scales deduced from turbulent and dispersive motions, makes the drag coefficient constant with height. If only proportionality to

the square of the mean wind is considered, the drag coefficient must be height dependent.

Finally it is worth to stress that these results are strictly valid only for the cube array configuration considered. However we believe that the knowledge of the behaviour of the flow in such simple configuration can guide the interpretation of more complex and realistic morphologies.

References

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