MODELLING THE FLOW WITHIN AND ABOVE THE URBAN CANOPY LAYER

Efisio Solazzo[1]*, Silvana Di Sabatino*[2] *and Rex Britter*[3]
[1] School of Geography, Earth & Environmental Sciences, University of Birmingham, Birmingham (UK); [2] Dipartimento di Scienza dei Materiali, Università di Lecce, Lecce (Italy)
[3] Engineering Department, University of Cambridge, Cambridge (UK)

ABSTRACT

The neighbourhood scale is recognised as being the connection between the street and the city scale. The present challenge in urban air quality context is the prediction, using simple models, of wind velocity profiles which take into account building morphology and layout. In this work a simple model to predict the spatially averaged flow field over real urban neighbourhoods is presented, based on the momentum balance between the inertial and the urban canopy layer. The buildings within the canopy were represented as a canopy element drag formulated in terms of the known morphological parameters λ_p and λ_f (the planar and frontal area density of buildings). These parameters were derived from a Digital Elevation Model (DEM). The nature of the model, being based on spatially averaged entities, is such that is suitable for inclusion into operational dispersion models for assessing urban air quality.

INTRODUCTION

Urban areas encompass a large number of neighbourhoods, which may in turn contain areas with similar surface characteristics. At a typical neighbourhood scale (up to about 5 km) the flow and pollutant dispersion can be modelled using spatially averaged approaches, where the buildings are considered as creating a region of porous resistance to the flow (*Britter, R.E. and S. Hanna*, 2003). In the present work, a simple model to estimate spatially averaged velocity profiles in real cities was adopted. Variation in height of λ_f, derived from the analysis of DEMs, was taken into account. The use of DEM methodology provided a powerful tool for a statistical treatment of the urban canopy layer in terms of morphological parameters. Capability of the model in modelling real flow patterns was evaluated using published data from wind and water tunnel experiments over array of cubes.

METHODOLOGY

The starting point of this work was the model introduced by *Cionco* (1969) for a vegetative canopy and successively adopted by *Macdonald, R.W.* (2000) for application to urban-type of roughness, intended as array of cubes. The model was based on the momentum balance between the urban canopy layer and the atmosphere above, expressed in terms of the drag force exerted by the buildings on the wind flow as:

$$\frac{d}{dz}\left(l(z)\frac{dU(z)}{dz}\right)^2 = \frac{C_D\,\lambda_f}{2H}U^2(z) \qquad (1)$$

where $l(z)$ is the mixing length, $U(z)$ the spatially averaged wind profile, C_D the drag coefficient, H the height of the roughness elements and λ_f the frontal area density impacted by the wind. Information about the planar area density λ_p are included into the expression for $l(z)$. Equation (1) allows an analytical solution for $z < H$ of the form

$$U(z) = U_H \exp\left(a\left(\frac{z}{H}-1\right)\right) \qquad (2)$$

once that the boundary conditions

$$U\,(z = H) = U_H\,;\; U\,(z = 0) = 0 \qquad (3)$$

are provided. Parameter a was empirically determined by *Macdonald, R.W.* (2000) for an array of cubes, $a \approx 10\ \lambda_f$.

It is possible to identify two main weaknesses in the approach described by Equations (1) and (2):

- U_H may results a poor choice of boundary condition, as it is set in the shear layer, characterised by large gradients of all measurable quantities. This is particularly true in real cities where velocity gradients are particularly large just at the top of the urban canopy. Besides, mean velocity itself is difficult to calculate meaningfully in the shear layer region being this strictly dependent on the building spatial distribution and morphometry of the neighbourhood area considered. Measurements in this region are generally problematic and also difficult to interpret.
- Secondly, arrays of cubes are too crude a simplification of a real urban canopy as the buildings in real cities have different shapes and heights. Building heights and building height variability affect the flow field. This cannot be neglected when modelling the flow over a real urban area.

Our Model

In our model equation (1) was solved numerically. Limitations described in section 2 were overcome

- by replacing the boundary conditions (3) with initial conditions at the top of the computational domain at $z = b\ H$ ($b > 2.5$), corresponding to the unperturbed region of the flow, well above the canopy layer and where most wind velocity measurements are available or where they can at least be obtained. The conditions were expressed in term of wind velocity and its first derivative, the latter being easily obtainable from the log-law profile in the inertial layer.
- by supplying a realistic description of the city geometry through the parameter λ_f in equation (1). This was done through the analysis of detailed building morphological data. As discussed in (*Ratti, C. et al.*, 2002), an image based analysis technique of DEMs can be used to obtain the required information, provided that the neighbourhood area has been correctly identified. In particular, the estimation of λ_f as a function of z is the key parameter to quantify the vertical building height variability over the neighbourhood area.

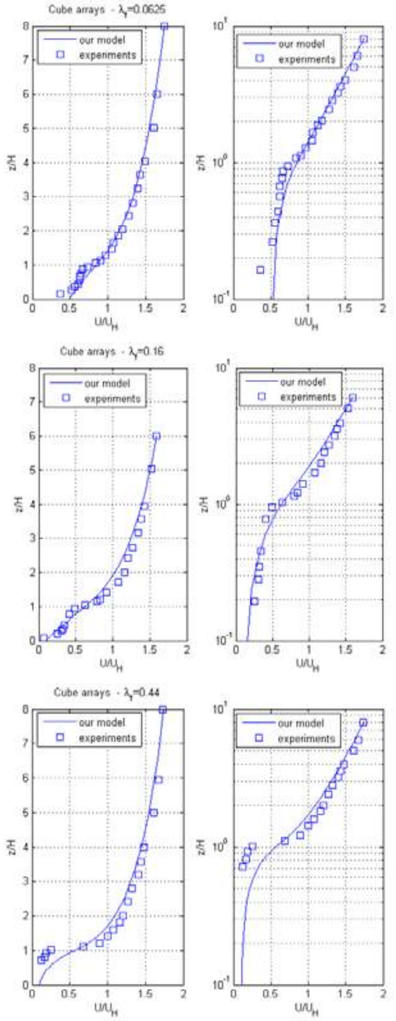
The resulting model has the advantage of being flexible and easily implementable, e.g. into fast response operational model for assessing urban air quality at neighbourhood scale. Further more, it includes the potential of the statistical description of urban area in terms of the morphological parameters λ_p and λ_f. In fact, being the model based on a ordinary differential equation of the form of (1), once assigned the initial conditions and the profiles of the building height trough $\lambda_f(z)$, only one solution is allowed. That same solution applies to all the neighbourhood areas characterised by similar morphological properties.

RESULTS

Evaluation of our model over array of cubes

The experimental data used to verify our model are those by *Macdonald, R.W. et al.* (2000) performed in a water flume. This study provides profiles of mean velocity, spatially-averaged mean velocity, turbulent intensities, and Reynolds stresses over cube arrays of different frontal area packing densities namely: $\lambda_f = 0.0625$, $\lambda_f = 0.16$ and $\lambda_f = 0.44$. These experiments were designed with the intention of studying different flow regimes in a sparse, intermediate and dense canopy which are representative, according to Oke's classification (*Oke, O.L.*, 1978) of isolated roughness, wake interference and skimming flow regimes, respectively.

Given the nature of our model we are only interested in spatially-averaged mean velocity profiles. The comparison between our model and the corresponding spatially-averaged measured wind profiles is shown in Figs. 1a, 1b,and 1c.



a)

b)

c)

Fig. 1; Comparison of our model with results from Macdonald R.W. et al. (2000), for a) λ_f = 0.0625, b) λ_f = 0.16, and c) λ_f = 0.44.

Results in Fig. 1 show that the agreement between our model and measurements is generally very good. The model shows a tendency to underestimate the velocity in the region above the building top and to overestimate it in the region below. The worst performance of our model is in the shear layer region. More precisely, for λ_f = 0.0625 (Fig. 1a), the model predictions conform very closely to those obtained from the experiment, except in the region near the building top and in proximity of the ground, where there is a tendency to overestimate the mean velocity. The case λ_f = 0.16 (Fig. 1b) shows that our model reproduces the experiment favourably. At the larger packing canopy density of λ_f = 0.44 (Fig. 1c) there is a slight overestimation which is more evident in a confined region close to the building top and in the in-canopy region. Overall, results confirm the capability of our simple model in predicting the averaged flow over complex geometries.

Application to real urban neighbourhoods

As discussed in section 'Our model', the use of $\lambda_f(z)$, calculated from DEMs by computing the frontal area of the built-to-unbuilt variation with height, is capable of handling the substantial difference between arrays of cubes and real city geometries. Fig. 2 shows λ_f (z) curves for London, Toulouse, Berlin and Salt Lake City.

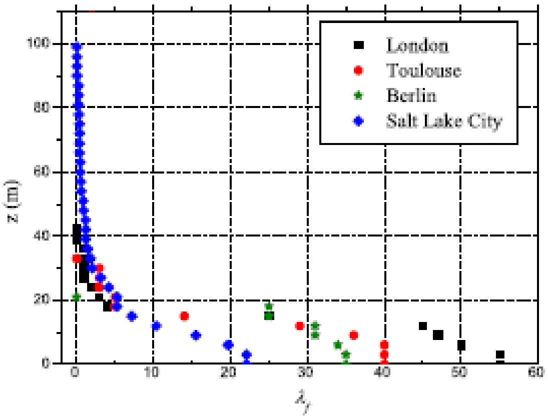


Fig. 2; λ_f curves for real neighbourhood areas.

Fig. 2 shows that some buildings in some of the investigated neighbourhoods tend to be less tall than long (e.g. London), whilst other cities are mainly characterised by high-rise city centres where skyscrapers are common (e.g. Salt Lake City). All these features were included in our model to account for the vertical spatial variability of the building height. Our model was then used to calculate spatially-averaged velocity profiles within and above real urban canopies. The velocity at 2.5 times the averaged building height was arbitrarily set to 5 m s^{-1}.

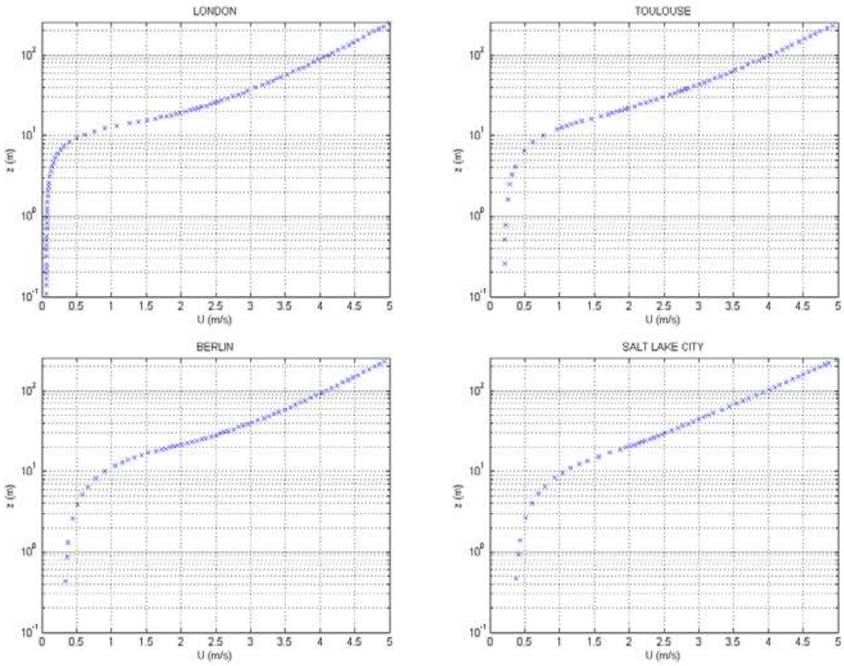


Fig. 3; Spatially-averaged velocity profiles for the urban neighbourhoods of London, Toulouse, Berlin, and Salt Lake City in logarithmic scale.

Besides spatially-averaged wind profiles, the coupled methodologies of DEMs and our model provided information on the displacement height, the roughness length and the friction velocity as reported in Table 1.

Table 1. Displacement height from DEMS and roughness length and friction velocity estimated from our model results.

	d (from DEMs) (m)	z_0 (m)	u_* (m s^{-1})
London	11.9	0.92	0.36
Toulouse	10.9	1.6	0.4
Berlin	12.1	1.06	0.37
Salt Lake City	11.4	2.0	0.42

Results in Table 1 show that larger z_0 values are related to city areas where u_* is also larger (e.g. Salt Lake City), although a direct correlation with the λ_f profiles does not appear to be straightforward. Further investigations are then required in this direction.

CONCLUSIONS

In this paper we have discussed an application of a model based on a balance equation between the obstacle drag force and the local shear stress, to produce spatially-averaged velocity profiles at neighbourhood scale. The buildings within the canopy are represented as a canopy element drag formulated in terms of the morphological parameters λ_f and λ_p. These parameters are obtained from the analysis of urban DEMs. The model was validated against available experimental data over cube arrays. The use of $\lambda_f\,(z)$ removed some difficulties present in previous models especially in the boundary conditions. Also it is a useful way of accounting for building height variability. Our model results obtained by use of real frontal area densities taken from the analysis of DEMs show promise as a simple tool for predicting spatially-averaged velocity profiles in real urban areas at the neighbourhood scale. The nature of the model is such that it is suitable for inclusion into operational urban air quality models. In fact, if the morphometry of a city is known the model only needs either a wind measurement (its derivative can be estimated by means of an iterative method) at a single height, or two wind measurements of which one could be in the logarithmic layer and the other within the urban canopy.

REFERENCES

Britter, R.E. and S.R. Hanna, 2003: Flow and dispersion in urban areas. *Annu. Rev. Fluid Mech.*, **35**, 469-496.

Cionco, R., 1965, A Mathematical Model for Air Flow in a Vegetative Canopy'. *J. Appl. Meteorol.* 4, 517-522.

Macdonald, R.W., 2000: Modelling the mean velocity profile in the urban canopy layer. *Boundary-Layer Meteorology*, **97**, 25-45.

Oke, T.R., 1978: Boundary Layer Climates. Methuena Co. Ltd., London.

Ratti, C., S. Di Sabatino, R. Britter, M. Brown, F. Caton and S. Burian, 2002: Analysis of 3-D urban databases with respect to pollution dispersion for a number of European and American cities. W*ater, Air and Soil Pollution*: Focus **2**, 459-469.