14.7 ADJUSTMENT OF A RURAL BOUNDARY LAYER TO A HEATED URBAN CANOPY

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1. INTRODUCTION

Urban areas affect regional-scale weather processes by altering the momentum, heat and moisture content of the atmospheric boundary layer. The boundary layer in turn drives the street-level circulations within urban areas, which again affect mixing into the boundary layer. These coupled interactions are not currently represented within regional-scale numerical weather prediction (NWP) models, which usually represent urban areas as regions of enhanced surface roughness only. What these NWP models are missing is a representation of the weather modification effects of urban areas.

With this application in mind an urban canopy model is being developed at the Department of Meteorology, University of Reading (UK) to represent the effects of drag and heating that urban areas exert both on the boundary layer above and the canopy layer below. The model is used to show how the boundary layer structure adjusts to an urban area. The results have implications for how the impact of the urban area relates to its size, which is important in siting measurement campaigns.

2. APPROACH

The approach is based on spatial and time averaging of the Navier-Stokes equations for the airflow within the urban canopy, as is usual in studies of plant canopies (See for example the review of Finnigan 2000).The averaging procedure gives a spatially averaged Reynolds stress term, a dispersive stress term due to spatial inhomogeneities, and a distributed drag term due to the aerodynamic resistance of the buildings. Experimental evidence suggests that the dispersive stress is two orders of magnitude smaller than the other terms (Cheng and Castro 2001) and it is therefore neglected here. The other two terms are parameterised as follows (Belcher *et al*. 2002).

A mixing length approach is used here to model the turbulent stress. Motivated by physically-based arguments, two variants are employed - a standard mixing length scheme (SML), where the mixing length $l = \kappa z$ and a diplaced mixing length scheme (DML), where $l = \kappa(z-d)$ above the canopy and l = constant within. The value of the constant mixing length within the canopy is simply chosen by requiring that the mixing length profile be continuous at the canopy top.

The drag term D is parameterised by summing up individual drag contributions due to each obstacle and averaging the total over the volume of air within the canopy. This gives $D = u^2/L_c$, where u is the mean wind speed and L_c is a length scale which can be related to the obstacle density and the drag coefficient c_d of a single obstacle. Note that here c_d is the sectional drag coefficient that relates the drag at height z to the average wind speed at that height. From drag data for flow over cubical arrays measured at Surrey (Cheng and Castro 2001), we estimate the value of c_d to be 2 for cubes.

The resulting momentum equations were solved numerically using the Met. Office code BLASIUS.

3. RESULTS

Numerical experiments were performed with the model to study (i) how the fully-adjusted flow above the canopy depends on the canopy characteristics and (ii) how the flow adjusts within the urban canopy. Sample results are presented below.

3.1 *Computation of Roughness Lengths*

The model was used to compute effective roughness lengths z_0 for fully-adjusted flow above a regular array of cubical obstacles. The DML version of the model was used here since the SML scheme is known to give unrealistically high values of z_0. Values of the displacement height d needed in the DML scheme were based on an empirical expression for d as a function of packing density due to MacDonald *et al.* (1998). The roughness length z_0 was then extracted from the computed log portion of the velocity profile. Results are shown for c_d =2 (as suggested by the Surrey data) in Fig.1, where comparisons are made with MacDonald *et al*.'s model (1998) and wind-tunnel data. It is indeed satisfying that the correct variation of z_0/h with roughness density is obtained by using these empirically-based values for c_d and d. This success in reproducing effective roughnesses in the limit of a fully adjusted flow provides strong validation of the canopy model, and warrants its application to a flow which is adjusting to a canopy, described below.

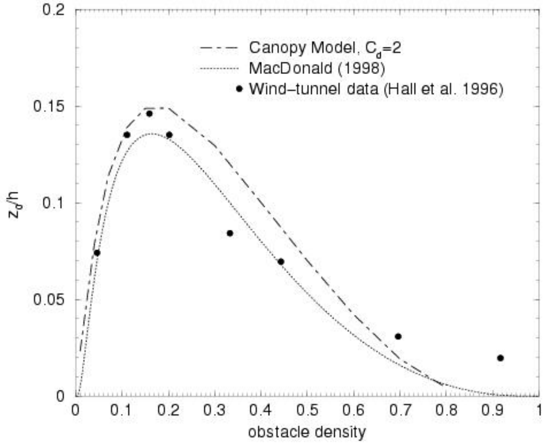

Fig.1: Roughness lengths computed from the model

3.2 Adjustment of Wind in the Urban Canopy

Linear analysis of the horizontally-averaged momentum equations with a canopy drag force $D = u^2/L_c$ shows that perturbations of the equilibrium velocity profile within a canopy decay on a distance that scale with L_c (Belcher *et al.,* 2002) This indicates that L_c may be thought of as a lengthscale for the wind profile to adjust within the canopy. To bear out these scaling arguments and determine this lengthscale precisely, numerical experiments were performed to compute the non-linear adjustment of an initially logarithmic rural wind profile to an urban canopy. Three different values of L_c were used. Vertical profiles of normalised horizontal velocity as a function of fetch from the leading edge of the canopy are shown in Fig. 2. Both SML and DML simulations indicate that the wind speed adjusts by a distance of $3L_c$. The present, fully-nonlinear model hence gives a precise value for the adjustment lengthscale that should prove useful in citing instruments in observational campaigns.

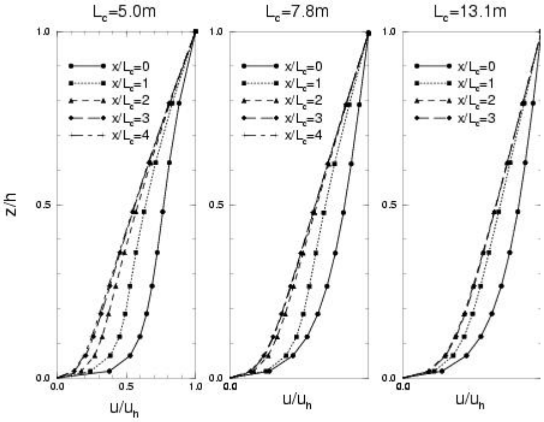

Fig. 2: Adjustment of mean wind profile in canopy

Comparisons of the present model with measurements of Davidson *et al.* (1995, 1996) and the linear theory of Belcher *et al*. (2002) are shown in Fig 3. Davidson *et al.* performed two sets of measurements using staggered arrays of obstacles. They measured the time-mean streamwise velocities at half canopy height at several locations in the cross-stream direction to compute lateral averages. SML and DML model runs were done using L_c values of 7.8m and 11m respectively, with d/h=0.24 (computed from MacDonald *et al*.'s empirical expression) in the DML run. These values of L_c correspond to drag coefficients of 5 and 3.5 respectively. The model gives very good agreement with the data. There is also excellent agreement with the linear theory except in the recovery region, where the linear calculation underpredicts the wind speed.

The values of c_d here were tuned so that the model best fitted the data. It is encouraging that the full model with the DML requires a value of $c_d = 3.5$, closer the the measured values of 2. Although the dispesive stress is small once the flow has adjusted to the canopy, we are currently investigating the possibility that the dispersive stress, associated with the large volumes of the cubes that make up the canopy, may decelerate the flow upwind of the array. Accounting for this process would then imply that a c_d = 2 would agree better with the data.

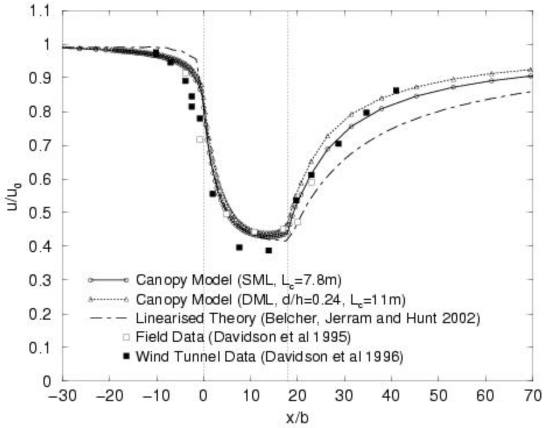

Fig. 3: Deceleration of mean wind through canopy

4. CONCLUSIONS

A nonlinear distributed drag model for urban canopy flow has been put together. The model successfully predicts the roughness length and the mean wind speed within arrays of regular obstacles. The mean wind in the canopy is shown to adjust on a lengthscale $3L_c$ which depends on obstacle density and drag coefficient. The model thus gives quantitative confirmation of linearised theory and shows promise for application in larger-scale NWP models. Further results on heated canopies and the effect of upstream boundary layer stability will be presented at the Symposium.

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5. REFERENCES

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