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ANALYSIS OF THE DYNAMICAL INTERACTIONS BETWEEN ATMOSPHERE AND URBAN CANOPIES OF DIFFERENT DENSITIES USING A DRAG FORCE APPROACH

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Abstract: The exchanges of momentum, heat and pollutants between the lower atmosphere and the urban canopy, as well as those inside the canopy layer, are strongly dependent on the building morphology and distribution and on the built density of the various districts. In order to properly represent the influence of the canopy on those transfers, a high resolution method is required. Our objective is to develop a method which is able to reproduce the mean flow features and turbulent statistics within and above the canopy at the city scale. At this scale, building-resolving methods are prohibited and the use of an atmospheric model is required to take into account the large atmospheric scales in a realistic way.

For that purpose, we use the Large-Eddy Simulation model ARPS which has been modified by Dupont and Brunet (2008a, 2008b) in order to investigate the interactions between forest canopies and the atmosphere. They introduced a drag force approach and showed that this method is able to accurately reproduce all the essential features of turbulent flows over plant canopies. For applications to urban areas, the method requires some modifications, mainly in the parameterisation of the drag force.

The drag term depends on the sectional drag coefficient (C_d). In most of the numerical work using a drag approach, a constant value of C_d is chosen for the whole canopy. However, this parameter should vary with height, and with area density (a_f) which, in turn, depends on the building morphology. The simulations presented in our study have been performed for various urban canopy densities and morphologies. For each type of canopy the values of C_d and their distribution within the canopy are different. The results are compared with mean wind profiles and turbulent statistics from measurements and direct numerical simulations, when available in the literature. Our study shows that using a C_d varying with height is necessary to reproduce the mean flow features and the turbulent statistics within and above canopies.

Keywords: *LES, urban canopy, drag approach, ARPS*

NOMENCLATURE

$F_{Di}(z)$ – drag force per unit volume [$kgm^{-2}s^{-2}$]
ρ – air density [$kg\ m^{-3}$]
$C_d(z)$ – sectional drag coefficient
$a_f(z)$ – frontal density per volume [m^{-1}]
u_i – wind velocity in i-direction [ms^{-1}]
λ_f – frontal density
λ_p – packing density
λ – cube (frontal or packing) density
l_i – cube length [m]
w_i – cube width [m]
h_i – cube height [m]
z – altitude [m]
dx - longitudinal grid size [m]
dy - transversal grid size [m]
H - canopy height [m]
z_0 – roughness length [m]
d – displacement height [m]

INTRODUCTION

Already in the 60's, the scientific societies were interested in the impact of urbanisation on the climate. In the 80's, the urban boundary layer was studied in detail (Oke, 1987), but the numerical tools which are necessary to simulate flow simultaneously at city scale and at the street scale were not invented yet. Several years later, the first numerical models were used in order to obtain knowledge about urban climate (Brown 2000). With informatics progress, the urban atmosphere investigations have developed but even nowadays informatics capacities are insufficient to compute the air flow of a whole city by solving explicitly the flow around buildings. Simplified cases of homogeneous canopies have been investigated by wind-tunnel experiences (Macdonald *et al.* 2000, Castro *et al.*. 2006), by direct numerical simulation (Coceal *et al.*, 2006), by large-eddy simulation (Kanda 2006, Kanda *et al.* 2004, Sabatino *et al.*. 2008) and by Reynolds Averaged Navier-Stokes models (Santiago *et al.* 2008). These studies have been performed for cube rows and for computational domains that do not exceed 8*H*. Therefore the aim of the present work is to show that air flows at city scale can be computed today by giving simultaneously precise information about the mean flow features inside of the canopy.

METHOD

The simulations were performed using the Advanced Regional Prediction System (ARPS) developed by the Center for Analysis and Prediction of Storms (CAPS, University of Oklahoma). CAPS is supported by the National Science Foundation and the Federal Aviation Administration under Grant ATM92-20009. This Large-Eddy Simulation model has been modified by Dupont and Brunet (2008b) by adding a drag term (equation 1) in the momentum equation:

$$F_{D_i}(z) = 0.5\rho C_d(z) a_f(z) u_i \sqrt{u_j u_j} \qquad (1)$$

The subgrid-scales are modelled by a 1.5 order turbulent closure scheme where a subgrid-scale turbulent kinetic energy equation is resolved. Their purpose was to simulate turbulent flows at very fine scale within and above homogeneous vegetation canopies. The results were validated against characteristics of turbulent flows over forest canopies that were previously observed in wind-tunnel and in-situ experiments. To adjust this method to urban canopies, the parameters a_f and C_d have to be redefined. a_f is given by the geometric properties of the canopy (equation 2) :

$$a_f(z)=\frac{\sum zl_i}{zdxdy-\sum l_i w_i z} \qquad (2)$$

The drag approach has already been used for urban canopies. C_d is usually considered as constant but in recent studies (Santiago *et al.*. 2008, Kono *et al.*. 2010) it was shown that this coefficient is height and density dependent. If the purpose is to produce accurate mean wind profiles inside of the canopy, this height dependency has to be taken into account in the choice of C_d values. For the simulations presented hereafter, the vertical C_d profiles were found by adjusting the profiles of longitudinal velocity with measured profiles (Macdonald *et al.*. 2000, Castro *et al.*. 2006) and obstacle resolving methods (Santiago *et al.*. 2008). The height dependant products of C_d and a_f that are used in the simulations are presented in Figure 1 for 4 densities ranging from 6.25% to 44%.

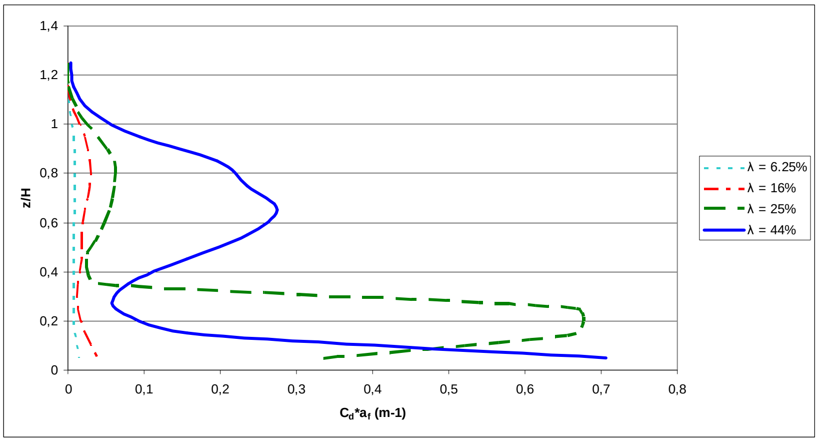

Figure 1: Product of sectional drag coefficient and frontal density per volume as function of the altitude for various packing densities.

NUMERICAL DETAILS

The physical domain size for all simulations is 2860m x 1460m x 1400m. The lateral boundary conditions are defined as periodic and the flow is forced by a constant geostrophic wind of 12.1 ms^{-1}. At the height of 1000m a Rayleigh layer is imposed in order to absorb the waves which could be reflected from the rigid top of the domain. The canopy is made up of cubes whose height is H=10m for all simulations. The cubes are homogeneously distributed in the canopy. In the case of cubes λ_f is equal to λ_p (equation 3), so we will simply talk about λ.

$$\lambda_p=\frac{\sum w_i l_i ?}{dxdy}=\lambda_f=\frac{\sum h_i l_i ?}{dxdy}=\lambda=\frac{\sum l_i ?}{dxdy} \qquad (3)$$

The horizontal size of grids is 20m. Tests of grid sizes of 10m, 40m, and 80m were performed. The finer the horizontal grid size, the smaller the differences between simulations. Within the canopy such differences can clearly be neglected. The vertical grid size depends on the altitude. Grids have a height of 1m from the bottom up to z/H = 2.5 (z = 25m). From 25m up to the bottom of the Rayleigh layer, grids are stretched by a hyperbolic stretching, in order to reach a mean vertical grid size of 25m over the whole domain. Inside of the Rayleigh layer the vertical grid size is 49m. Tests of vertical grid size have also been performed in order to check if the high velocity gradients just above the canopy are correctly simulated.

The time step is fixed at 0.03s. A turbulent flow reaches statistical steady state when a simulation lasts 6 times the large-eddy turn-over time. In this case, this corresponds to 12,000s. All simulations lasted 16,200s, where the last 3,600s composed of 181 data files were used in the statistical analyses. For one simulation, nearly 190 single processor CPU hours were used. The evolution in time of mean velocity and shear stress profiles were verified to ensure statistical convergence.

RESULTS

The values of C_d are chosen in order to fit the normalized longitudinal velocity profiles on profiles from literature. The comparisons of these normalized profiles are shown in figure 2. Using a height dependant C_d allows accurately reproducing the profile of U/U_H within the canopy for the densities of 16% and 25%. In the case of λ = 6.25% the simulated wind profile is much more smoothed than the profiles from Macdonald *et al.* (2000) experiment so that discrepancies appear near the top of the canopy (z/H = 0.7 and 0.8). For the density λ = 44%, experimental data could not be found in the literature. Results from the obstacle resolving RANS method (Santiago *et al.*, 2008) were chosen to fit the curve. The accuracy of the ARPS simulation is quite satisfying. It is worth noting that both numerical and experimental results differ from profiles deduced from the analytical models (Sabatino *et al.*, 2008) that cannot reproduce the profiles shape in the lower part of the canopy.

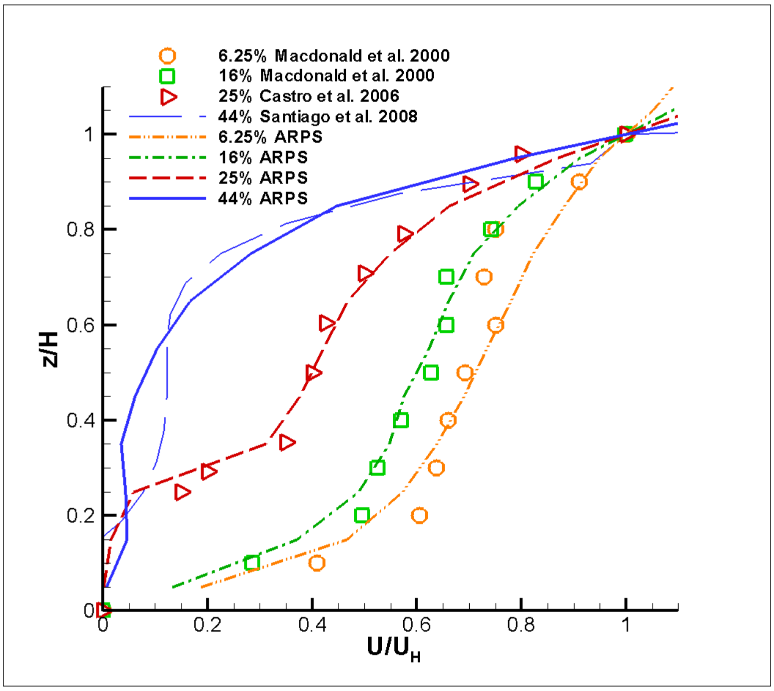

Figure 2: Normalized vertical velocity profiles for the 4 densities

The drag term (equation 1) resulting from the imposed values of C_d and a_f (Figure 1) and from the simulated velocity, normalized by its averaged value over the whole canopy, is illustrated in figure 3. In order to avoid numerical problems, very small drag force values have been added above the canopy (Figure 1). In reality, the value of the drag term should be 0 above z/H = 1. It can be observed that the maximum values of the normalized force appear just below the top of the canopy. This is in agreement with the numerical results of Kono *et al.* (2010) for different cube densities. Above z/H = 0.8 the normalized drag force increases with canopy density. Near z/H = 0.7 and beneath this trend is inversed due to the large decrease of wind velocity and to higher values of mean drag force with increasing density (Figure 2): the less dense canopy produces the greatest normalized drag force. These trends are also confirmed by Kono *et al.* (2010). However the values beneath z/H = 0.2 are about 1 when the drag force is determined by pressure difference measurements.

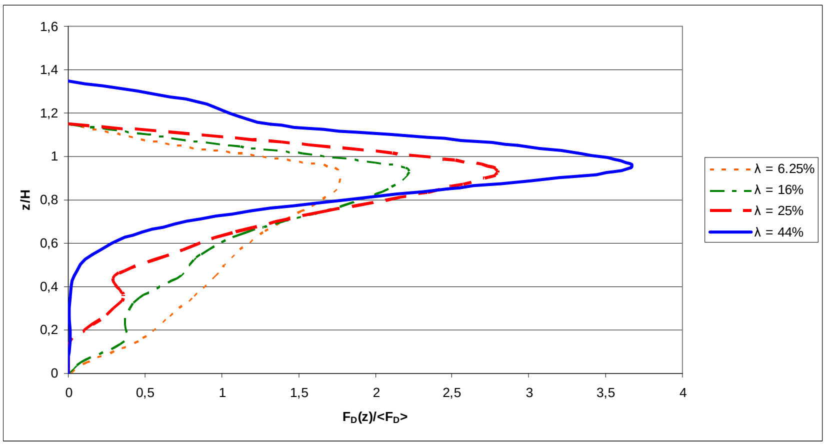

Figure 3: Vertical profile of drag force per volume normalized by the mean drag force, comparison of the 4 densities.

The influence of the canopy description on the above atmosphere is also examined. The roughness parameters z_0 and d obtained by a linear regression of the wind profile in the roughness sublayer were compared to results of Macdonald *et al.* 1998 (table 1). The values for the less dense canopy are in good agreement. Concerning the other densities, 30% differences are found. Comparing to the results of several studies (Hagishima *et al.*, 2009), it can be observed that roughness parameters for a given density may vary by 300% from one study to another, so that we can conclude that our study gives quite good results. This is confirmed by the velocity profiles above the canopy (Figure 4) which fit very well with the logarithmic law by using the roughness parameters from table 1.

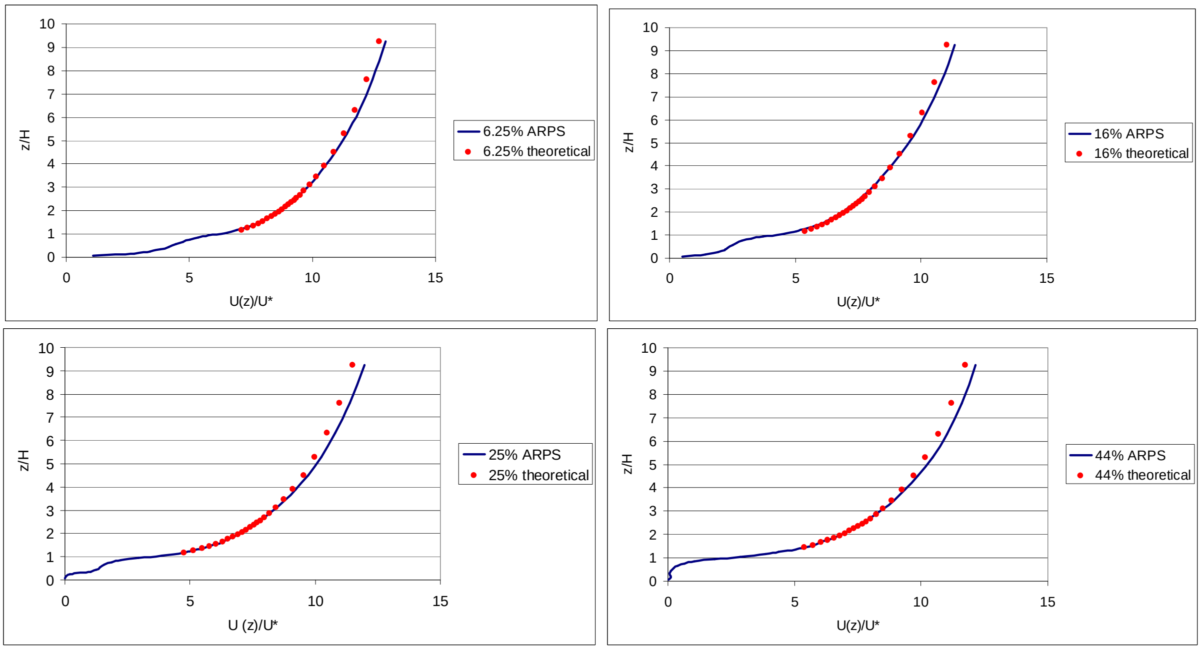

Figure 4 : Comparison of the longitudinal velocity profile computed by ARPS and a theoretical logarithmic profile with same roughness parameters: a) λ = 0.625%, b) λ = 16%, c) λ = 25%, d) λ = 44%.

Table 1: Roughness parameters z_0 and d in comparison with results of Macdonald *et al.* 1998:

	λ =0.0625	λ = 0.16	λ = 0.25	λ = 0.44
z_0/H - Macdonald *et al.* 1998	0.06	0.13	0.13	0.06
z_0/H LES A	0.06	0.11	0.09	0.08
d/H - Macdonald *et al.* 1998	0.18	0.32	0.5	0.7
d/H LES A	0.18	0.2	0.57	0.79

CONCLUSIONS AND PERSPECTIVES

It is shown that the choice of a height and density dependant sectional drag coefficient leads to longitudinal velocity profiles that are close to profiles obtained by wind tunnel measurements and obstacle resolving methods within the canopy. The validity of the method above the canopy is shown by the well fitting logarithmic profile.

The simulation area will be extended and simulations of flow above and within heterogeneous canopy will be computed. Therefore canopies with several areas of different densities and different canopy height will be investigated. The further aim of these studies is to simulate flow within and above the city of Nantes which will be divided in town quarters with mean geometric characteristics.

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