MULTI SCALE BUILD-UP AREA INTEGRATION IN PARALLEL SWIFT

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Abstract: Parallel SWIFT is used in the AIRCITY project to model the air quality at a few meters resolution over the whole Paris area. Hence, it is crucial to provide the capability to correctly handle the downscaling from meso scale modelling to local scale modelling over build-up areas. Build-up areas have directional specificities due to the orientation of streets, or also the river Seine for the Paris case, that lead to directional bulk effects.
To overcome this, we have developed an approach based on directional drag coefficients. Drag coefficients of buildings within their neighbourhood are derived once and for all for a set of wind directions. A methodology has been implemented in Micro-SWIFT to derive this, but data obtained from other CFD models can be used. This static database of drag coefficients is then used to create directional matrices of Cionco type canopy densities, at the wished resolution. The capability to handle and create canopy laws according to the flow direction has been implemented in SWIFT. Results are presented on test cases.

Key words: *urban canopy, Cionco, directional drag coefficient database, SWIFT, Micro SWIFT.*

INTRODUCTION

PMSS, Parallel-Micro-SWIFT-SPRAY (Oldrini et al., 2011), is a fast transport and dispersion modelling system. It is designed for local scale and takes into account buildings. The parallel version can be run on multi core computers or large parallel clusters. MSS consists of SWIFT and SPRAY used in urban mode (Micro SWIFT, Micro Spray).

SWIFT / Micro-SWIFT (Moussafir et al., 2004; Tinarelli et al., 2007) is an analytically modified mass consistent interpolator over complex terrain. Given topography, meteorological data and buildings, a mass consistent 3-D wind field is generated. It is also able to derive diagnostic turbulence parameters to be used by SPRAY / Micro-SPRAY. Micro-SPRAY is an LPD (Lagrangian Particle Dispersion) model able to take into account the presence of obstacles. It directly derives from the SPRAY code (Anfossi et al., 1998; Tinarelli et al., 1994 and 2000). It is based on a 3-D form of the Langevin equation for the random velocity (Thomson, 1987).

Parallel SWIFT / Micro SWIFT is used in the AIRCITY project (Moussafir et al, 2013) to model air quality at a few meters resolution over the whole Paris area. Hence, it is crucial to provide the capability to correctly handle the SWIFT downscaling, from meso scale modelling to local scale Micro SWIFT modelling, especially over build-up areas. The model has to transition smoothly from the larger scale where the flow is mildly impacted by buildings, with very few model levels in the canopy, to the local scale. Secondly, the capability to transition horizontally will allow for efficient nested dispersion modelling: transition is needed between the inner domain, where buildings have explicit flow influence, to a nested outer domain with larger grid steps, but still taking into account building influence on the flow. This capability is crucial for small computational cluster of a few cores where the fine resolution grid can only be handled on a part of the whole city.

CANOPY LAWS AND DIRECTIONNAL CANOPY DENSITY

Introduction to canopy laws

Canopy models were first introduced to model vegetative canopy, see for instance Cionco (1965). Macdonald (2000) introduced the canopy approach to handle regular arrays of cubical obstacles. More recently urban canopy models are developed to take into account more precisely the influence of buildings in model where buildings are not explicitly resolved by the mesh.

Following Cionco (1965), a canopy flow is defined by three parameters: the canopy height h_c and its roughness z_0, and the canopy density a. The canopy is divided into three layers, depending on the height above ground z. For a neutral layer, the wind profile u is:

For $z < z_0$: $$u(z) = 0 \quad (1)$$

For $z_0 < z < h_c$: $$u(z) = u^* / k \; ln((h_c - h_d + z_0) / z_0) \; [(1-Fc) \, ln((z + z_0) / z_0) / ln ((h_c + z_0) / z_0) + Fc \, exp(a (z / h_c - 1))] \quad (2)$$

For $h_c < z$: $$u(z) = u^* / k \; ln((z - h_d + z_0) / z_0) \quad (3)$$

With :

$$F_c = 1 - exp(- 4 a^2 / (1 + 2 a))$$
$$h_d = 0.7 \, F_c \, h_c$$

Influence of buildings

The building mechanical influence on the flow is taken into account through the canopy density on a layer related to the average height of buildings. Build-up areas in cities have directional specificities due to patterns in the orientation of streets, leading to directional bulk effects. In order to take into account this directional effect, we have integrated a directional canopy density in SWIFT.

The directional density is derived for any wind direction, and for a specified horizontal grid, from the drag coefficients of buildings located in each grid cell. The drag coefficient c_d is defined as the force of the flow on the building in the wind direction F_u normalized by the static pressure $0.5 \rho u^2$ and the frontal area of the building A_f:

$$c_d = F_u / (0.5 \rho u^2 A_f) \quad (5)$$

A database of drag coefficients for a particular city and for a set of wind directions is used as input. This database has to be constituted from any model that is able to compute the drag coefficients of each individual building, but within its surrounding, and for buildings all over the whole city. The database is stored in a static file, like a building database or a landuse file, but with a dependency on wind directions.

The capability to compute drag coefficients was added to Micro-SWIFT in order to build a drag coefficient database for a full city. For a set of wind directions, Micro-SWIFT computes the wind field over the city with a few meters resolution. The pressure field is then calculated from the wind field (Armand et al, 2010). The drag of the flow for each building is then computed from the pressure force, making the assumption that the viscous stress is small compared to the pressure force. Micro-SWIFT integrates the pressure force on each grid level and for every facades of each building.

DERIVATION OF CANOPY PROPERTIES

The main parameters to define are the canopy height h_c and the canopy density a. The available inputs are the geometrical description of buildings and the directional drag coefficient database.

The canopy height h_c is directly derived by the building geometrical data. Here, a ground surface weighed average of the building heights has been chosen.

The methodology described here is taken from Coceal et al (2004). The canopy density a is derived through the basic formulation used by Cionco (1965) to obtain the exponential law within the canopy layer. The following equation describes the balance in the canopy between Reynolds stress per unit of area and the obstacle drag force.

$$d(\,(\,l(z)\;\; du/dz\,)^2) = \Sigma\; 0.5\; c_d\,(z)\;\; u^2\, A_f\;\; dz\;\; /\,(\,A_t\, h_c\,) \qquad (6)$$

Where $l(z)$ is a mixing length, $c_d\,(z)$ is the sectional drag coefficient that has an effective aerodynamic frontal area $A_f\; dz\,/\,h_c$, A_f being the frontal area of each building, and A_t is the total averaging area. In our situation A_t is the horizontal grid cell area. The sum is over the buildings in the grid cell.

The Cionco exponential profile is an analytical solution of this equation when assuming that $l(z)$ and $c_d\,(z)$ are constant along z in the canopy layer.

The mixing length is estimated using Coceal et al (2004) with the canopy height h_c, the displacement height of canopy d and the Von Karman constant κ:

$$l = 0.5\;\kappa\;(h_c - d) \qquad (8)$$

$$d = h_c\;(\,1 + A^{-\lambda p}\;(\lambda_p - 1)\,) \qquad (9)$$

Where λ_p is the plan area density defined as $\lambda_p = \Sigma A_p\,/\,A_t$, A_p being the ground area of each building, and A is an empirical constant set to 4.

Finally, the canopy density a is then expressed as following:

$$a^3 = h_c^3\;\sigma_f\,/\,(2\;\; l\,) \qquad \text{with } \sigma_f = 0.5\;\Sigma\;(\,c_d\, A_f\;)\;\;/\,(A_t\, h_c\,) \qquad (10)$$

This methodology has been implemented in a SWIFT pre processor called DENCAN.

APPLICATIONS ON MACDONALD REGULAR CUBE ARRAYS

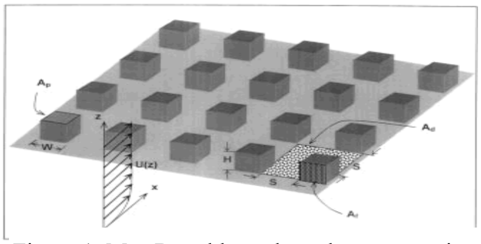

Figure 1. Mac Donald regular cube array setting

Flows around regular cubic configurations have been studied in Macdonald (2000) for various canopy densities. The canopy formulation described above was compared against these wind tunnel experiments. The flow around 10 m cubes spaced by 15 m (λ_f=0.16) is computed in a 500 m square domain with two configurations: configuration 1 has a horizontal spatial resolution of 1 m and obstacles effects are seen explicitly (standard Röckle formulation of Micro-SWIFT). Configuration 2 has a horizontal spatial resolution of 50 m and obstacles effects are seen through the directional urban canopy implemented in SWIFT. The directional urban canopy has been computed with a drag coefficient database obtained with the configuration 1.

One steady state meteorological computation is performed in a few minutes for configuration 1 on an average laptop: the mesh is quite large and the parallel capability of SWIFT has not been switched on. Due to the coarse mesh, configuration 2 runs in a few seconds.

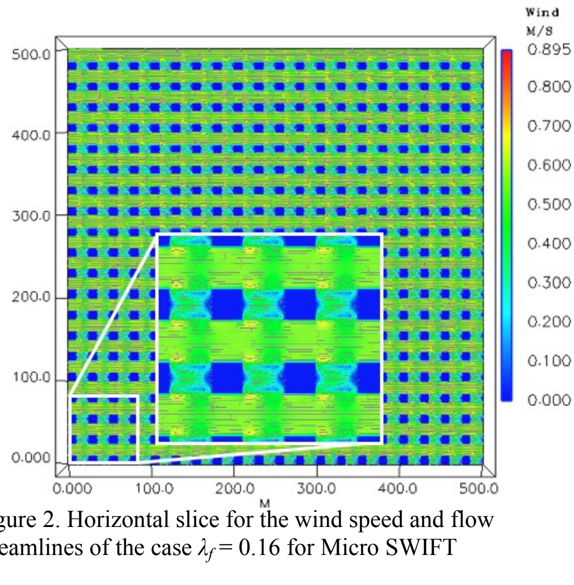

Figure 2. Horizontal slice for the wind speed and flow streamlines of the case $\lambda_f = 0.16$ for Micro SWIFT

To compare the results of these two configurations, and also the wind tunnel data, a spatial average of the horizontal velocity is done for configuration 1.

Comparisons have been performed between the two configurations for various reference winds, changing wind intensity and direction. Figure 3 shows the horizontal wind profile for the Micro-SWIFT average and the SWIFT canopy parameterization for two wind directions. The two configurations, macro scale and micro scale, show very good agreement for the two wind directions.

Figure 3 illustrates also the modification of the canopy wind according to the wind direction. The change of the wind speed in the canopy due to the wind direction can not be neglected in this regular setting: a flow aligned with the array of buildings has an average value of 0.6m/s at 5m, whereas this value drops to 0.2m/s for a 45° wind direction.

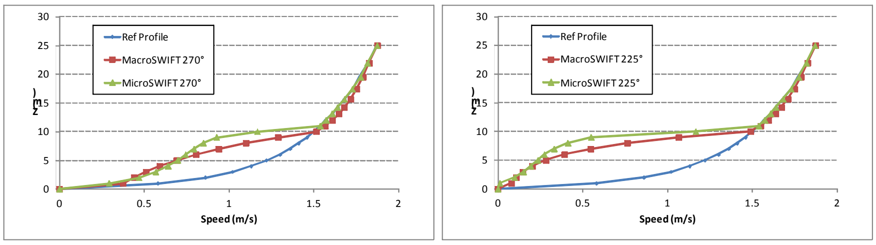

Figure 3. Vertical profiles of horizontal wind velocity – Free flow (blue) / Micro SWIFT explicit buildings (green) / SWIFT directional urban canopy (red) – Main flow direction aligned with cube arrays (left) / 45° off cube array direction (right).

Comparisons have also been performed with Macdonald wind tunnel measurements. Figure 4 displays, in order of magnitude, a good agreement between wind tunnel data and SWIFT computations for density λ_f=0.16. It should be noticed that wind tunnel data have a specific spatial averaging due to scarcity of measurements.

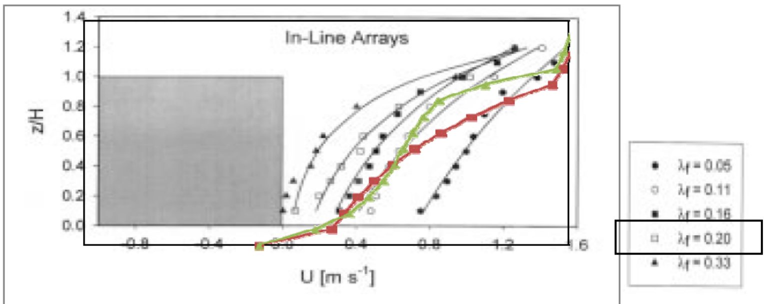

Figure 4. Vertical profiles of horizontal wind velocity – Spatial average of wind tunnel measurements for different λ_f (black and white dots) / SWIFT for λ_f =0.16 with explicit buildings (green) and directional urban canopy (red)

CONCLUSION

A capability to take into account directional urban canopy data has been incorporated into SWIFT. This capability shows realistic agreement on regular cubic settings for various wind directions. A methodology to derive directional canopy density from a database of directional drag coefficients and building geometrical data has also been implemented in a SWIFT pre processor, called DENCAN.

The constitution of the directional drag coefficient database can be performed by any model that can compute the flow around the buildings within their surrounding for various wind directions. Micro-SWIFT is able to derive this database over large urban domains due to its parallel capability.

In the framework of the AIRCITY project, additional testing will be performed on realistic city data from Paris with more variance of building shapes and heights.

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