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# Evaluation of building energy use: from the urban to the building scale

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Dated: 15 June 2015

**Abstract**

A 1-D canopy interface model (CIM) has been developed recently and integrated in the meso-scale meteorological WRF v3.5 model in order to improve the surface representation. One of the objectives of such a model is to prepare for the coupling of micro-scale models with meso-scale models so as to improve building energy consumption estimates at the urban scale as well as improve meteorological variables calculation in urban canyons.

The objective of the present study is to evaluate the value of the use of a module able to produce highly resolved vertical profiles of these variables. We will discuss the strategy that will be used to couple the WRF system with the CitySim software. The one-way coupling methodology for the WRF-CIM-CitySim is detailed here.

It is expected that the WRF-CIM system can provide enhanced meteorological profiles to CitySim and that this can hence improve the energy consumption calculation at the building scale. This coupled system, could be used by urban planners or architects, as it would provide a significant advantage in the evaluation of building energy use and urban planning scenarios. Future work will focus on a two-way coupling in order to improve the feedback response in the meteorological model.

Keywords: building energy-use, canopy model, meso-scale models, micro-climate, multi-scale modelling, urban climate.

## 1. Introduction

It is now well known that building energy demand and urban climate are closely related and interdependant (Ashie, Thanh Ca, et Asaeda 1999; Salamanca et al. 2011). The urban climate depends on a series of processes taking place at different spatial (from global to local) and temporal scales (Oke 1982). Meteorological mesoscale models were initially dedicated to weather forecasting without the need to detail interactions between urban areas and the atmosphere (Salamanca et al. 2011). In the last few years, urban parametrizations have been integrated in these mesoscale models to also simulate urban heat islands (UHI) (Masson 2000; Kusaka et al. 2001; Martilli, Clappier, et Rotach 2002), building energy consumption (Krpo et al. 2010, 201; Salamanca et al. 2010)) and air pollution at the urban scale (Salamanca et al. 2011). The underlying purpose is thus to develop systems that could help urban planners make decisions and propose sustainable urban planning scenarios to decrease UHIs, building energy demand, or urban air pollution.

However using mesoscale meteorological models, with a high resolution, to cover a whole urban area and resolving at the same time local building effects and urban heat islands is still not feasible with actual computer performances (Martilli 2007). Moreover the use of available microscale models (such as Envimet (Bruse et Fleer 1998)or EnergyPlus (Crawley et al. 2008) or CitySim (Kämpf et Robinson 2007; Robinson 2012; Robinson et al. 2009)) on more than a neighborhood (few streets) is also not feasible. Such models are also often forced with average annual climatic conditions in the evaluation of energy consumption with data coming for example from the METEONORM software (Remund et al. 1995). Thus exchanges between buildings and the atmosphere are often not very precise. Multiscale modeling is hence proposed as a solution.

In a previous study (Mauree 2014), a new one-dimensional canopy interface model (CIM) was developed in an offline mode and that it could produce high-resolution vertical profile for wind, potential temperature and humidity. Furthermore it was integrated to the meteorological mesoscale model WRF (Skamarock et al. 2008) to improve the surface representation in such models.

In the present study, it is proposed, as a first step towards multi-scale modeling, to couple the CitySim model with the CIM. Instead of using average annual weather file with the meteorological data, WRF is run with the traditional BEP-BEM model providing the meteorological parameters. CIM is then used to calculate high resolution vertical wind and temperature profile to modify the simulation of the building energy balance done within the CitySim software.

In the next section we will describe the methodology used to couple CIM to CitySim. We then describe the experiments we used to compare results from the WRF-CIM-CitySim system. We then briefly conclude and develop the perspective of the multiscale modeling from the regional to the building scale.

## 2. Methodology

We describe hereafter the methodology used to couple CitySim and CIM.

### Brief description of CIM

A one-dimensional Canopy Interface Model was developed (Mauree 2014) to improve the surface representation in mesoscale meteorological models and also to prepare the coupling with microscale models.

CIM uses a diffusion equation derived from the Navier-Stokes equations but reduced in one direction only. EQUATION 1 and 2 are used to calculate the wind speed and potential temperature profiles.

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{dz}\left(\kappa_t \frac{\partial\theta}{\partial z}\right) + f_\vartheta^s \quad (1)$$

$$\frac{\partial U}{\partial t} = \frac{\partial}{dz}\left(\mu_t \frac{\partial U}{\partial z}\right) + f_u^s \quad (2)$$

where $U$ is the horizontal wind speed in either the *x*- or *y*-direction, $\theta$ is the potential temperature, $\mu_t$ and $\kappa_t$ are the momentum and heat turbulent diffusion coefficients and $f_u^s$ and $f_\vartheta^s$ are the source terms representing the fluxes that will impact the flow.

CIM solves for a 1.5-order turbulence closure using the turbulent kinetic energy (TKE). The TKE is calculated using EQUATION 3:

$$\frac{\partial E}{\partial t} = \frac{\partial}{\partial z}\left(\lambda_t \frac{\partial E}{\partial z}\right) + C_\varepsilon^* \frac{\sqrt{E}}{l}\left(E_{stat} - E\right) + f_e^s \quad (3)$$

where $E$ is the TKE, $\lambda_t$ is the diffusion coefficient (assumed here to be equal to $\mu_t$), $C_\varepsilon^*$ is a constant equal to 1, $E_{stat}$ is considered to be a stationary value of the TKE and $f_e^s$ is source term representing the additional production of TKE due to the obstacles.

The momentum and heat diffusion coefficients are calculated using:

$$\mu_t = C_\mu \sqrt{E} l \quad (4)$$

$$\kappa_t = \frac{C_\mu \sqrt{E} l}{\Pr} \quad (5)$$

where $C_\mu$ is a constant equal to 0.3 and *l* is the mixing length from Santiago and Martilli (2010) and adapted by Mauree (2014).

CIM has been developed to function in an offline mode and can hence be forced at the top using traditional meteorological boundary conditions. For the purpose of this study, the model is forced by using meteorological data coming from the WRF (Skamarock et al. 2008) model.

**Brief description of the CitySim software**

CitySim (Kämpf et Robinson 2007) is a large-scale dynamic building energy simulation tool developed at the Ecole Polytechnique Fédérale de Lausanne (EPFL). The tool includes an important aspect in the field of many buildings simulation: the building interactions (shadowing, light inter-reflections and infrared exchanges). Furthermore, CitySim is based on simplified modelling assumptions to establish a trade-off between input data needs, output precision requirements and computing time.

**Coupling Strategy**

Figure 1 describes the coupling between CIM and CitySim

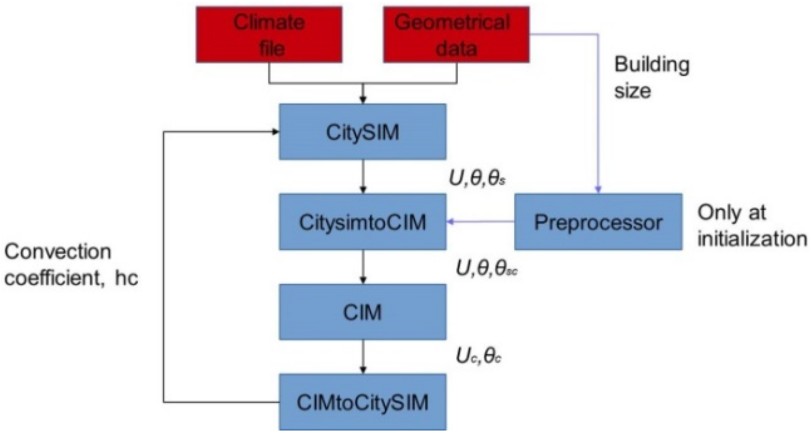


*Fig 1:* Coupling strategy flowchart

At the initialization stage, CIM needs to read the geometrical data from the CitySim XML file. This is then used to calculate the buildings size and height.

Figure 2 describes how these obstacles (building as well as vegetation) are then integrated in the model with possible variation of the obstacle sizes along the vertical. The characteristics are used to calculate the horizontal $(\hat{\varphi}_h)$ and vertical $(\hat{\varphi}_{vert})$ surfaces of the obstacles and their volumes $(\hat{\phi})$ as well as surfaces $(\varphi)$ and volumes $(\phi)$ porosities at each of the level *l.*

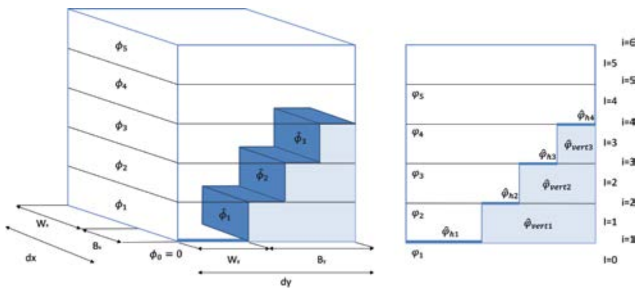

*Fig 2*: Surface and volume characteristics

The surfaces and volumes calculated, for each grid cell, are used to influence the diffusion process and appear in the discretized form of the equation. EQUATION 6 gives an example for the momentum. More details on this can be found in Mauree (2014).

(6)

$$U_I^{t+1} = U_I^t + \Delta t \frac{\varphi_i}{\phi_I} \mu_t \frac{U_{I-1} - U_I}{\Delta z} - \Delta t \frac{\varphi_i}{\phi_I} \mu_t \frac{U_I - U_{I+1}}{\Delta z} + F_u$$

where *I* and *i* are the index for the cell centre and faces respectively and $F_u$ is the integral over the volume of the source terms.

In the next steps, CitySim initializes its calculation and provides the surface temperature ($\theta_s$) for each surfaces to CIM. CIM aggregates these surface temperatures for each level and for the *x*- and *y*-direction separately. As CIM can function in an offline mode, it can also read the same climate data as used by CitySim. Using the diffusion equations, CIM then calculate a profile for each of the meteorological variables (wind speed, temperature and humidity).

CitySim does not require precise meteorological variable itself, but rather the convection coefficient ($h_c$). The module CIMtoCitySIM thus calculates a new $h_c$ that can then be used by CitySIM to improve its calculations. The coefficient, based on McAdams (Mirsadeghi et al. 2013), is calculated as follows:

$$h_c = 2.8 + 3U \qquad (7)$$

where *U* is the wind speed calculated based on the wind attack angle on a surface in the windward or leeward-direction.

In order to conserve the properties of the physical parameters in CitySim, we then calculate a $h_c^*$ using the “new” air temperature profile:

$$h_c^* = \frac{h_c(\theta_i - \theta_S)}{\theta_C - \theta_S} \qquad (8)$$

Finally, these $h_c^*$ are then fed back to CitySim and used as an input for the next time step.

## 3. Experiments

The experiments are carried out over a region next to the city of Lausanne and we look more particularly at the LESO building on the EPFL campus in Ecublens, Switzerland. We assume the building has a size of 40m by 40m and a height of 9.6m. The WRF model is run over four domains centred over the coordinates 46.5N and 6.6E. The horizontal resolution of the domains from the coarser to the larger domain is 45km, 15km, 3km and 1km respectively (see Figure 3). The model is run for the month of December 2010.

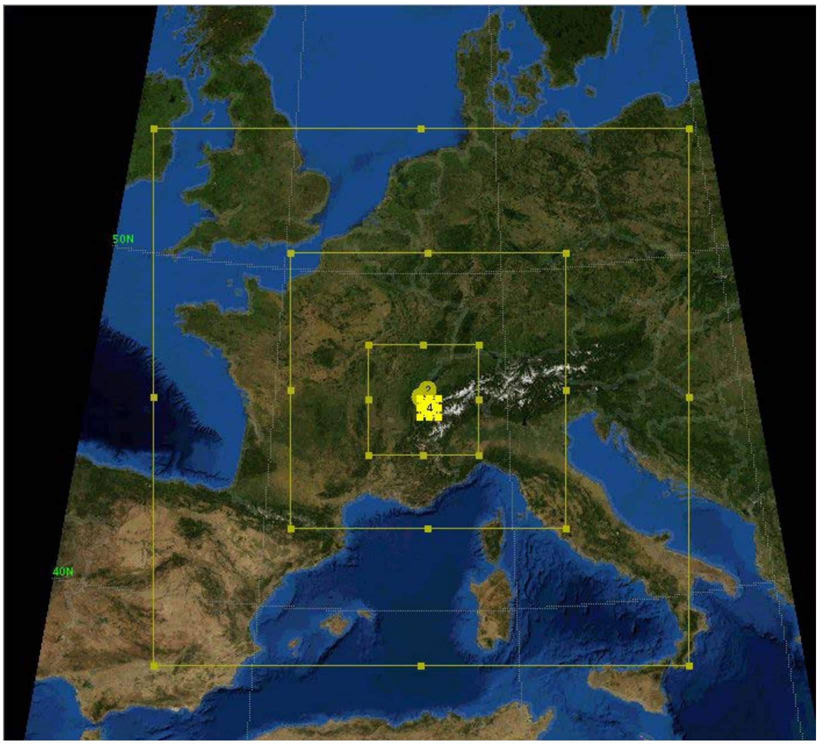


*Fig 3:* Domains used for simulation for WRF model (from WRFDomainWizard)

The data obtained from the WRF model are then used to forced CIM at the top, as was demonstrated by Mauree (2014).The CIM-CitySIM coupling is then evaluated with an analysis of the energy consumption of the LESO-PB building during 14 days in the month of December.

## 4. Results and Discussions

Figure 4 and Figure 5 show respectively the temperature and wind speed as calculated by CIM when forced using the WRF model and the temperature usually used by CitySim from the METEONORM software.

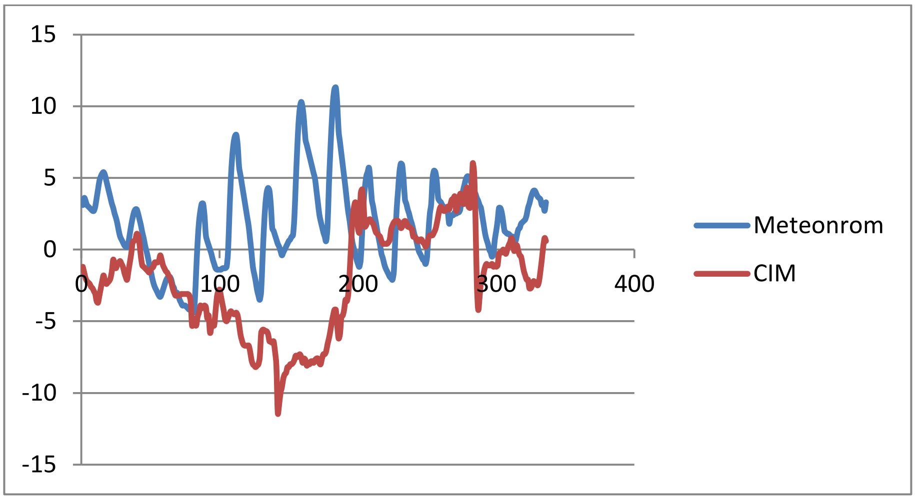


*Fig 4*: Temperature ($^{o}$C) for the 14 days of simulation

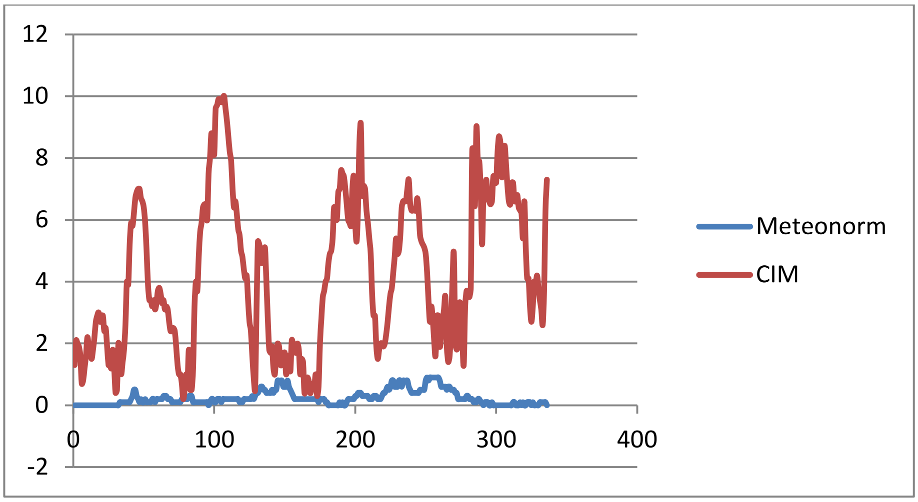


*Fig 5*: Wind speed (ms$^{-1}$) for the 14 days of simulation

It can be noted from the figures above that the wind speed is very different from the two datasets that are used. When using CIM although the outside air temperature has a standard deviation of 3.8$^{o}$*C,* the wind speed that is calculated by the CIM model is very different as compared to that obtained from the Meteonorm software. This can be explained by the fact that the data from the Meteonorm software is an average over 10 years for on particular meteorological station. The data obtained from CIM issued from the WRF model are validated against measured data obtained from a monitoring station on the LESO-PB and results are not shown here.

The CitySim and CIM coupling are also validated and are presented in a different study. Finally, we compute the energy consumption using the “new” (from CIM) and “old” meteorological dataset (from Meteonorm).

| | **Energy consumption (kWh/m$^{2}$)** |
|---|---|
| **Meteonorm** | 19 |
| **CIM** | 25 |
| **Difference (%)** | 30 |

*Table 1:* Energy consumption from the LESO-PB building

## 5. Conclusion and Perspectives

The need for precise calculation and justification of standard such as Minergie or BBC, is becoming increasingly important so as to evaluate with an enhance accuracy energy consumption of buildings. Based on this a new methodology was developed to perform a one-way coupling between the WRF model, the CIM software and the CitySim tool.

It was shown that when using traditional datasets such as Meteonorm, there can be an underestimation of both the air temperature and the wind speed. As building energy simulation tools, such as CitySim often make use of these datasets, they can hence predict lower energy consumptions.

It is expected in the future, to continue this work to provide a complete two-way coupling. Mauree (2014) already integrated the CIM in the WRF model and thus improving the surface representation in meteorological model. The two-way coupling should provide a better estimation of the anthropogenic heat consumption and greenhouse gas emissions in urban areas and could be a useful methodology in the assessment of urban planning practices and scenarios.

## Acknowledgment

The authors wish to thanks The Commision for Technology and Innovation of the Swiss Confederation for the funding of the Swiss Competence Center for Energy Research, Future Energy Efficiency Buildings and Districts (FEEB&D). We would like to thank Silvia Coccolo for the LESO geometrical files.

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