MULTI-SCALE MODELLING TO IMPROVE CLIMATE DATA FOR BUILDING ENERGY MODELS

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ABSTRACT

The recent AR5 report from the Intergovernmental Panel on Climate Change has again stressed on the need for mitigation and adaptation measures to tackle issues related to climate change. Tackling future urban planning and energy efficiency in the building sector is crucial as they account for almost 40% of energy use in developed countries.

A one-dimensional canopy interface module (CIM) was recently developed to improve the surface representation in meteorological models and to enhance boundary conditions for building energy models. In the present study, we explain the methodology to couple CIM to the CitySim software. We show that CIM can be used to provide high-resolution vertical profiles to improve the calculation of the energy balance.

INTRODUCTION

It is now well known that building energy demand and urban climate are closely related and interdependant (Ashie et al., 1999; Salamanca et al., 2010). 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 et al., 2002), building energy consumption (Krpo et al., 2010; 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 informed 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; Christen et al., 2009). Moreover the use of available microscale models (such as Envimet (Bruse and Fleer, 1998) or EnergyPlus (Crawley et al., 2008) or CitySim (Kämpf and Robinson, 2007; Robinson, 2012) 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. Thus exchanges between buildings and the atmosphere are often not very precise or even considered. 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 it was shown that it could produce high-resolution vertical profile for wind, potential temperature and humidity. Furthermore it was integrated in 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. This should provide high-resolution vertical wind and temperature profile to improve 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 validate the performance of CIM with experimental data and how we compare results from the CitySim-CIM system with traditional datasets. We then briefly conclude and develop the perspective of the multiscale modeling from the regional to the building scale.

METHODOLOGY

Before giving a description of the methodology used to couple CitySim and CIM, we first describe briefly these two models.

Brief description of CIM

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

$$\frac{\partial U}{\partial t}=\frac{\partial}{dz}\left(\mu_t\frac{\partial U}{\partial z}\right)+f_u^s \qquad (1)$$

$$\frac{\partial \theta}{\partial t}=\frac{\partial}{dz}\left(\kappa_t\frac{\partial \theta}{\partial z}\right)+f_\vartheta^s \qquad (2)$$

where U is the horizontal wind speed in either the x- or y-direction, θ is the potential temperature, μ_t and κ_t are the momentum and heat turbulent diffusion coefficients and f_u^s and f_ϑ^s are the source terms representing the fluxes (from the surface or buildings) 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:

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

where E is the TKE, λ_t is the diffusion coefficient (assumed here to be equal to μ_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:

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

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

where C_μ is a constant equal to 0.3. l is defined as the mixing length and is taken from Santiago and Martilli (2010) and adapted by Mauree (2014) to account to the obstacles density and height in the canopy.

CIM has been developed to function in an offline mode and can hence be forced directly at the top using traditional meteorological boundary conditions.

Brief description of the CitySim software

CitySim (Kämpf and 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.

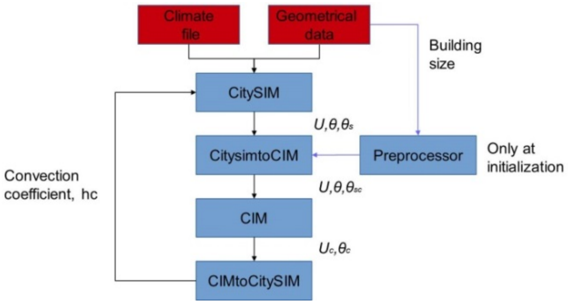

Figure 1: Coupling strategy flowchart

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 (width and breadth for each floor) and the height.

Figure 2 describes how these obstacles (buildings as well as vegetation) are then integrated in the model with possible variation of the obstacle sizes along the vertical (Kohler et al., 2012). The horizontal $(\hat{\varphi}_h)$ and vertical $(\hat{\varphi}_{vert})$ surfaces of the obstacles and their volumes $(\hat{\phi})$ as well as surfaces (φ) and volumes (ϕ) porosities are calculated at each of the level *I*. These variables are used to calculate the fluxes generated by the buildings.

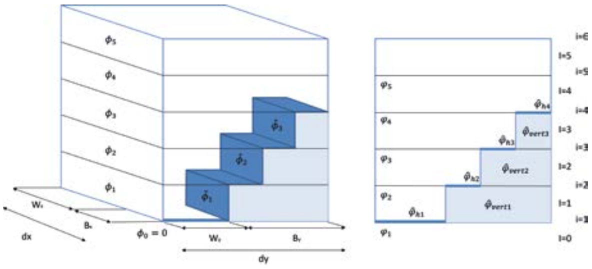

Figure 2: Surface and volume characteristics

Compared to previous studies, the surfaces and volumes calculated, for each grid cell, also influence the diffusion process and appear in the discretized form of the equation. EQUATION 6 gives an example for the momentum.

$$U_I^{t+1} = U_I^t + \Delta t \frac{\varphi_i}{\phi_I} \mu_t \frac{U_{I-1} - U_I}{\Delta z} - \Delta t \frac{\varphi_i}{\phi_I} \mu_t \frac{U_I - U_{I+1}}{\Delta z} + F_u \tag{6}$$

where I and i are the indices for the cell centre and faces respectively. F_u is the integral over the volume of the source terms and represents, for example, the drag forces from vertical surfaces and the shear from horizontal surfaces. More details on these source terms for each of the variables ($U, \theta\ and\ E$) can be found in Mauree (2014).

In the next steps, CitySim initializes its calculation and provides the surface temperature (θ_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 use the same meteorological data traditionally forcing the CitySim simulation. Using the diffusion equations CIM then calculate a profile for each of the meteorological variables (wind speed, temperature and humidity).

CitySim does not require a precise profile for meteorological variable, but rather uses a convection coefficient (h_c). The module CIMtoCitySIM thus calculates a new h_c with the high-resolution meteorological profiles. The McAdams formulation for the coefficient (Mirsadeghi et al., 2013), is calculated as follows:

$$h_c = 2.8 + 3U \tag{7}$$

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

In order to conserve the properties of the physical parameters in CitySim, we then calculate a pseudo "h_c^*" using the “more resolved” air temperature profile (θ_I) and the value used by CitySim (θ_C):

$$h_c^* = \frac{h_c\ (\theta_I - \theta_S)}{\theta_C - \theta_S} \tag{8}$$

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

EXPERIMENTS

Two separate experiments are carried out over the LESO building on the EPFL campus, Ecublens, Switzerland. We assume that the building has a size of 40m by 40m and a height of 9.6m (equivalent to 3 floors).

(a) To test the capacity of CIM to integrate the building characteristics and to calculate a highly resolved meteorological profile, we first make a simulation for a period of 5 days during the month of July 2013. The CIM is forced at the top using real meteorological data. For every time step CIM is run until a stationary solution is obtained. The wind speed is validated at a height of 2m, 10m and at 49m. As for the temperature, we compare with measurements at the surface (0.05m) and at the top of the canopy (49m).

(b) The CIM-CitySIM coupling is then evaluated by comparing the wind speed and the air temperature around the LESO-PB building during a typical month of December. When running CitySim a pre-heating period of 9 days is needed. The Meteonorm Ecublens climate file (Remund et al., 2010), typically used for the boundary conditions of CitySim, is also used to force the CIM at the top.

RESULTS AND DISCUSSIONS

CIM on LESO

CIM is first run as a stand-alone module to test its capacity to reproduce the wind and temperature profile in an urban canopy.

Figure 3 and Figure 4 show the time-series for the wind and temperature. It can be seen here that although the correlation is not very high, CIM is able to capture the main characteristics of the meteorological variables.

Table 1: Statistical analysis of the simulation over the 5 days at LESO.

	R2	Mean bias	R.M.S.E
U at 49m	0.58	0.96	0.14
U at 2m	-0.01	0.20	0.03
PT at ground	0.79	0.97	0.12

It can be seen however from Figure 5 and Table 1 that at 2m there is a very poor correlation between the simulated value and the observed data. This might be due to the variability of the wind with very low intensity and to the drag force parameterization used. Other studies have also shown difficulties in estimating the wind speed close to the ground (Santiago and Martilli, 2010).

If we look more closely at the high-resolution profiles that have been calculated by the CIM (see Figure 6), we can see on the contrary that there are significant period where the wind speed is well represented and in agreement with measured data.

CIM-CitySIM coupling

In order to evaluate the coupling between CIM-CitySim, we look at the variation in the meteorological variables.

Figure 7 shows the wind speed from the original climate file from Meteonorm and the one calculated from CitySim at 10m. It can be seen from this figure that the wind is significantly lower in the case when it is coming from CIM. This will influence hence significantly change the calculation of the convection coefficient as it is directly proportional to the wind speed.

Furthermore, from Figure 8, it can be noted that due to the lower wind speed, the temperature is generally higher close to the surface. We compared here the average temperature over the first 3 layers as these are the layers where the buildings are integrated and will also influence the convection coefficient.

CONCLUSION

A new methodology has been developed to couple a building energy model and a canopy interface model (CIM). CIM is a 1D model with the ability to reproduce the surface layer processes and can calculate high-resolution vertical profile using a diffusion process.

When using traditional climate files in building simulation models, there can be a significant overestimation of the wind speed, as the wind speed usually used is measured at 10m.

It has hence been proposed, on the one hand, to use the CIM model to calculate high-resolution vertical profiles for the wind speed and temperature in the canopy. These new profiles can then be used to calculate a pseudo convection coefficient for the building energy simulation software CitySim. On the other hand, CitySim can provide improved surface temperature calculations to CIM in order to enhance the calculation of the surface fluxes and thereby improving the building representation.

Future studies will be conducted to see what is the sensitivity of the model with respect to the calculated energy consumption. Preliminary analysis showed that this changed the energy consumption by 6%. Additionally, the complete coupled system from the meso-scale model (WRF) to the building energy simulation model (CitySim) is expected to further enhance the capabilities of the different models and could help in defining better urban planning practices. Better estimation of the energy consumption and evaluation of the thermal comfort of the inhabitants are crucial to build better buildings and cities.

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Figures

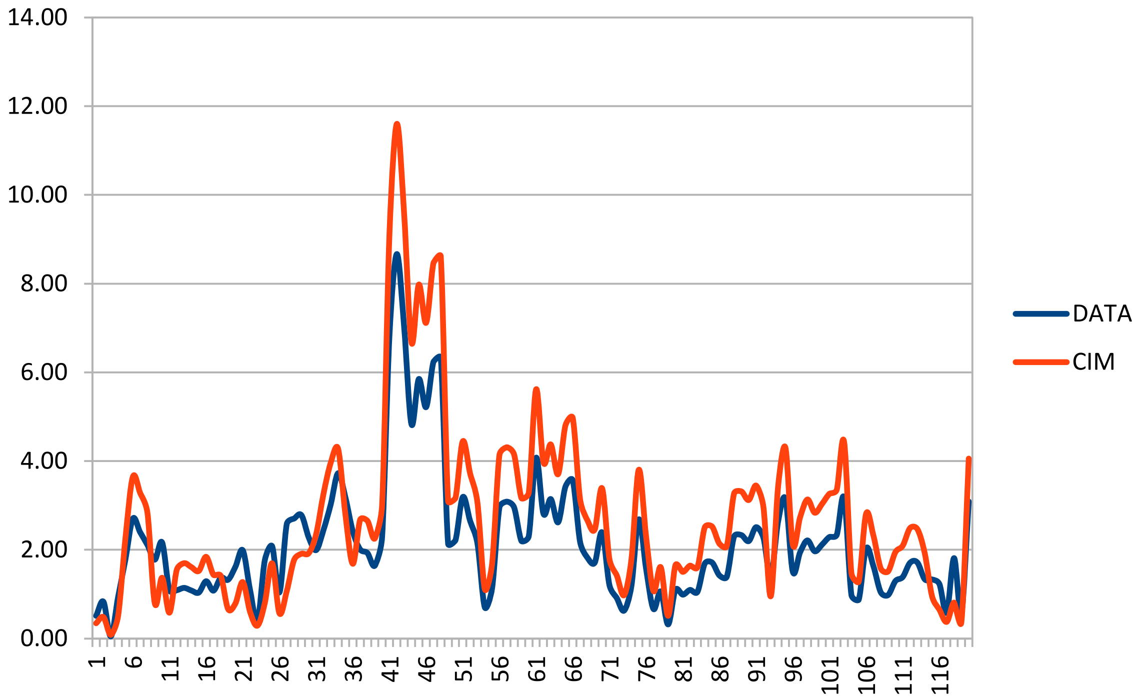

Figure 3: Time-series for the wind speed in (m s^{-1}) for the 5 days of simulation at 49m

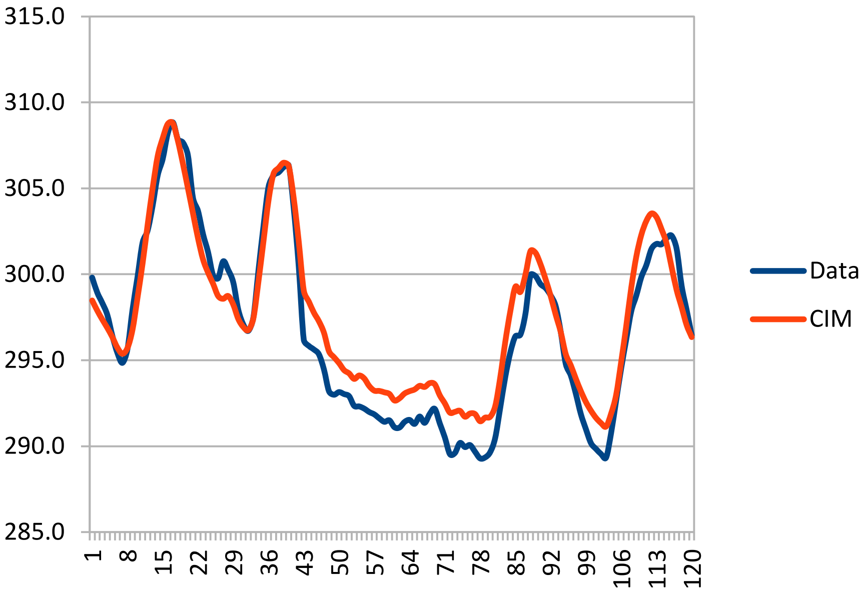

Figure 4: Time-series for the potential temperature in (K) for the 5 days of simulation at ground surface

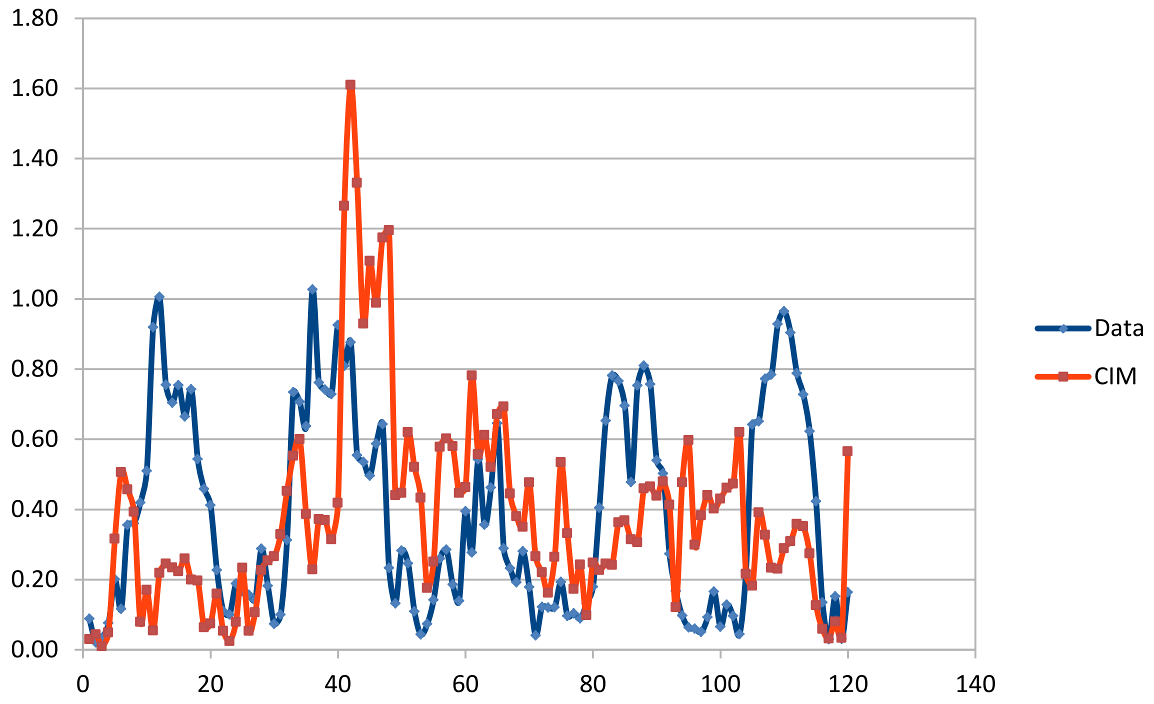

Figure 5: Time-series for the wind speed in (m s^{-1}) for the 5 days of simulation at 2m

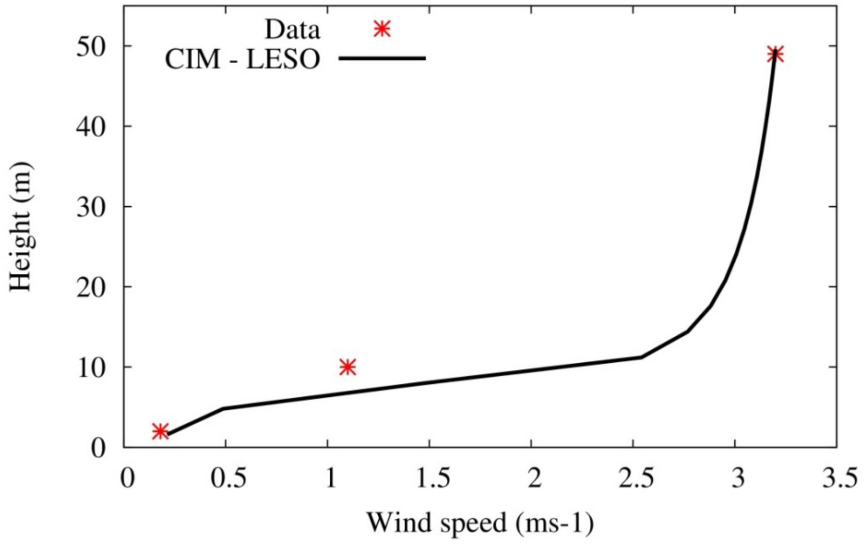

Figure 6: Vertical profile for the wind speed (m s^{-1}) compared with the measured data.

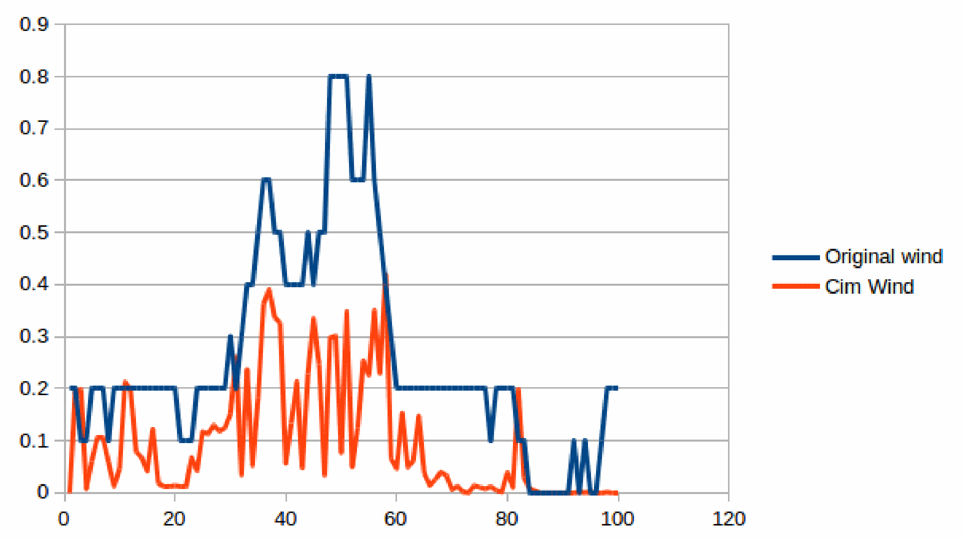

Figure 7: Wind speed (m s^{-1}) at 10m for 100 time steps from the original climate data and from CIM

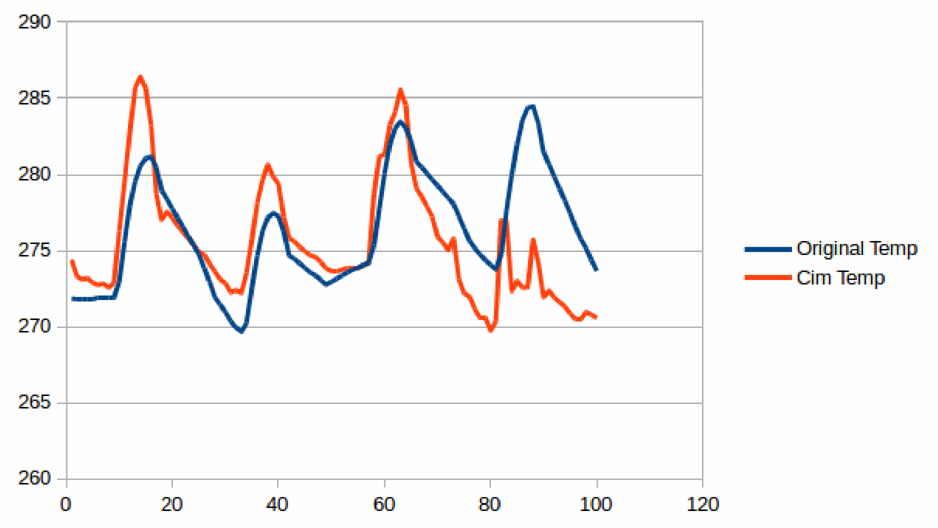

Figure 8: Average air temperature over the first 3 levels of the CIM compared with the original temperature from the climate file for 100 time steps