MULTI-SCALE MODELLING TO ASSESS HUMAN COMFORT IN URBAN CANYONS

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Abstract

As the impact of climate change progresses, heat waves are expected to increase significantly in the future. Coupled with the urban heat island effect, this will tend to have a major impact on the comfort of the inhabitants in urban areas. It is thus crucial to adopt the necessary sustainable measures and development scenarios to improve city liveability and human health. The main physical parameters that affect the outdoor human comfort are the air temperature, the relative humidity and the wind speed. Various tools, such as CFD or LES models, have been used in the past to evaluate these variables for the calculation of human comfort indices. These tools however are computationally too expensive and require extensive resources and data. Moreover, in our previous studies on the outdoor human comfort realized with the CitySim software, the meteorological variables were not linked to the urban form, geometry and roughness.

To overcome these barriers, the CIM (Canopy Interface Model) was developed to calculate high-resolution vertical profiles of meteorological variables. The CitySim software to perform energy and temperature simulations then used these outputs. In this study, virtual pedestrians were located in two different areas of the EPFL campus, in Lausanne (Switzerland): a natural environment - characterized by clay soil and cherry trees - and an artificial environment, the new asphalt square near the SwissTech Convention Centre. The analysis carried out with the CitySim software compares the outdoor human comfort of pedestrian with the wind data from the traditional Meteonorm dataset, and the new CIM wind simulations. A sensitivity analysis of the results shows the difference between both simulations, quantifying the impact of the new wind model in the calculation of the indices.

Keywords:
Multi-scale modelling, human comfort, urban planning, urban microclimate

1 INTRODUCTION

The current observed rise in global air temperatures will also have a significant impact on human health. The IPCC [1] pointed out in their last report that it is extremely likely that heat waves will increase in the future. Heat waves have been associated with heat strokes, hyperthermia and increased mortality rate especially among vulnerable population. The 2003 heat wave in France is an example of the dramatic consequences [2,3]. Besides, the urban areas are even more at risk as they are already subject to higher temperatures due to the urban heat island phenomena [4,5]. This is due to the absorption of solar radiation by the increased number of surfaces, the trapping of heat in urban canyons and the modification of wind patterns. The urban environment affects the outdoor human comfort, showing the impact of the urban form in the human thermal perception [6]. Different software exists to analyse the outdoor human comfort, for example ENVI-met, SOLWEIG and RayMan, and are able to quantify pedestrian thermal perception within the city environment.

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Several models and parameterizations schemes have been developed in the past to represent the effect of urban areas. CFD or LES models have been used but they are computationally expensive. Recently a Canopy Interface Model (CIM) [7] has been developed and coupled with the CitySim software [8,9].

A previous case study was performed to propose a new methodology to quantify the outdoor human comfort in the built environment, with the COMFA* thermal budget, by the use of the software CitySim [10]. For the purpose of this study, we improved the previous case study, by using the Canopy Interface Model to analyse the wind speed at 1.5 meters of height, in selected built environments. The proposed paper shows the impact of the wind speed on the outdoor human comfort, by evaluating the pertinence of using the traditional data or with the specifically calculated data.

The paper first briefly describes the computation of the wind using the CIM and the outdoor human comfort by the COMFA* thermal budget. The experimental setup is given in Sect. 3; the results are then presented and discussed in Sect. 4. We finally conclude and give a few future perspectives for this study in Sect. 5.

2 METHODOLOGY

2.1 Wind profile by the Canopy Interface Model

A one-dimensional Canopy Interface Model was recently developed [7] 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 is used to calculate the wind speed in both directions (we only show the equation for the *x*-direction).

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

where *U* is the horizontal wind speed in either the *x*- or *y*-direction, μ_t is the momentum turbulent diffusion coefficient and f_u^s is the source term representing the fluxes (from the surface or buildings) that will impact the flow.

The momentum diffusion coefficient is calculated using:

$$\mu_t = C_\mu \sqrt{El} \qquad (2)$$

where C_μ is a constant equal to 0.3 and E is the turbulent kinetic energy (TKE). *l* is defined as the mixing length and is taken from [11] and adapted by [7] to account for the obstacles density and varying building height in the canopy.

The boundary conditions at the top of CIM is forced using an extrapolated value from the Meteonorm meteorological dataset. The ground surface temperature calculated by CitySim [12] is used as an input for the CIM model. The wind profile is calculated along the vertical axis in both u and v directions in each cell with a resolution of 3m. The wind speed computed at 1.5 m above the ground will then be used as an input parameter in CitySim to quantify the outdoor human comfort, by the COMFA* budget.

2.2 Outdoor human comfort

The outdoor human comfort is analysed by the COMfort FormulA (COMFA* Budget) and is expressed in W·m^{-2}. The fundamental equation that describes COMFA* model [13] is:

$$B = M + R_{RT} - C - E - L \qquad (3)$$

where *M* is the metabolic heat generated by a person, R_{RT} are short and long wave radiations absorbed, *C* is the sensible heat lost by convection, *E* is the evaporative heat loss through perspiration and *L* is the long-wave radiation emitted by a person. All fluxes are expressed in (W ·m^{-2}). The thermal sensation scale of COMFA Budget is defined in Table 1.

COMFA Budget (W·m^{-2})	Thermal Sensation
≤ -201	Cold
-200 to -121	Cool
-120 to -51	Slightly cool
-50 to +50	Comfort
+51 to +120	Slightly warm
+121 to +200	Warm
≥+201	Hot

Table 1: COMFA budget (W ·m^{-2}) as function of thermal sensation.

Pedestrian are modelled with the software CitySim, further details concerning the methodolgy are available in a previous case study [10].

3 EXPERIMENTAL SETUP

The outdoor human comfort is calculated on two selected areas of the EPFL campus: the new square near the Swiss Tech Convention Centre (Case study A) and a natural environment that host a “bocce” court (Case study B); the location of the selected environments is defined in Fig. 1. The two sites are commonly used by students and workers of the university during the daytime as nice environments for discussions and relaxation.

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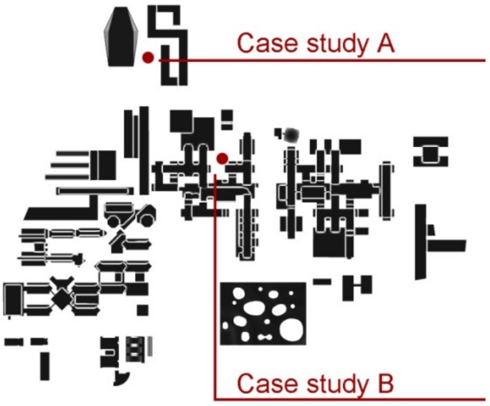

Fig. 1: EPFL campus in Lausanne, selected outdoor environment where the outdoor human comfort is defined: the new square near the Swiss Tech Convention Centre (Case study A) and a natural environment that host a "bocce" court (Case study B).

4 RESULTS AND DISCUSSIONS

4.1 Wind profile by the Canopy Interface Model

The wind profiles determined by the CIM are computed from an extrapolated value from Meteonorm. Figure 2 gives an example of three profiles for three particular days for the STCC study case. The profiles simulated with CIM (black cross) taking into account the presence of obstacles has a much lower wind speed as compared to the one coming from Meteonorm (dotted line). This is due to (i) the drag force which significantly reduces the wind speed when vertical surfaces are present in the canopy and (ii) the modification of the mixing length that was calculated based on the density and height of obstacles. The wind speeds at the top of the column do not correspond because, on the one hand, when using the Meteonorm dataset the value computed at 10m height is used over the whole column. On the other hand, when using CIM, a value is calculated for every cell (20 cells of 3m each) in the column. Above the building height (30m), the wind speed increases rapidly to reach the Meteonorm value.

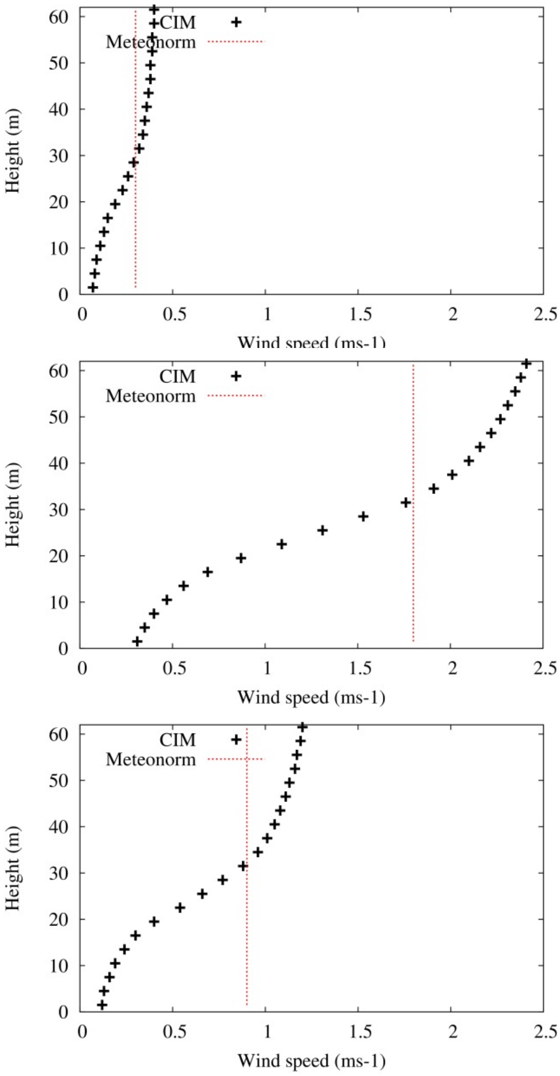

Fig. 2: Vertical profile of the wind speed (ms-1) for (from top to bottom) 21st March, 21st June and 21st of December; in dotted red – Meteonorm data; black cross – CIM profiles.

Figure 3 (a, b and c) gives a daily wind speed profile provided by Meteonorm and calculated by CIM in the square near the Swiss Tech Convention Centre, for the 21st of March, 21st of June and 21st of December and which will be used in the COMFA* Budget. As expected the urban geometry impacts the wind speed which is reduced compared to the one provided by Meteonorm. Additionally, the wind speed provided by Meteonorm is given for a 10 m height while on the contrary the one calculated by our methodology is defined at 1.5m height, corresponding to the centre of gravity of the human body. The wind speeds are higher during the daytime and lower during the night-time, this can be explained by the turbulent fluxes that appear in contact with heated surfaces; as an example during the 21st of June the maximal wind speed during the daytime is 0.3 m/s, and lower than 0.1 m/s during the night-time.

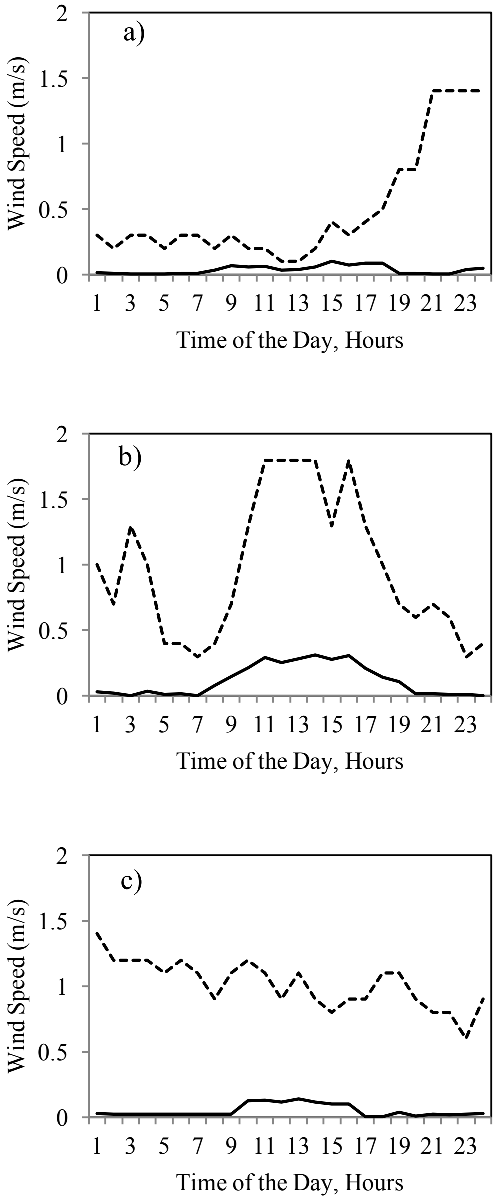

Fig. 3: Wind speed provided by the software Meteonorm (dotted line) and calculated by the Canopy Interface Model (continuous line) for the square near the Swiss Tech Convention Centre. a) 21st of March. b) 21st of June. c) 21st of December.

The wind speed (not shown here), as calculated by the CIM in the bocce court, is drastically reduced, with a yearly average speed of 0.01 m/s due to the density of the built environment.

4.2 Outdoor human comfort

The outdoor human comfort was calculated with the weather data provided by the software Meteonorm and with the Canopy Interface Model. Figure 4 shows the COMFA* Budget for the 21st of March, 21st of June and 21st of December for a pedestrian located near the Swiss Tech Convention Centre. The thermal sensation perceived by the pedestrian varies with the weather data: the pedestrian is facing a hot thermal sensation from 12 to 17 hours, if using the weather data provided by Meteonorm. However hot thermal sensation will increase by one hour if using the CIM data model, passing from warm to hot at 11 am. This is related to the wind speed, that changes from 1.0 m/s in average during the day (with a maximal speed equal to 1.8 m/s) to an average speed of 0.1 m/s (with a maximum speed equal to 0.3 m/s). During the 21st of March there is no difference in thermal perception during the daytime, just during the night-time when the maximum difference between the wind speeds is 1.4 m/s. The difference between the two models is lower during the winter solstice, when the perceived thermal sensation is constantly lower in the CIM model during the day and night time.

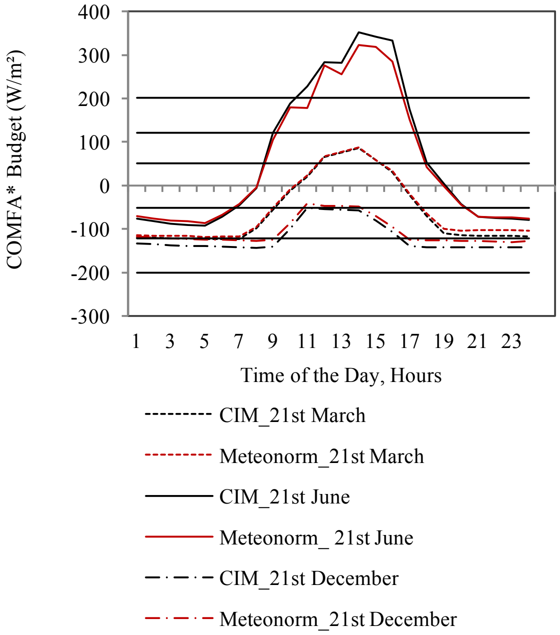

Fig. 4: COMFA energy budget for the square near the Swiss Tech Convention Centre, during the 21st of March, 21st of June and 21st of December. Comparison between weather data provided by Meteonorm (Red) and calculated by CIM (Black).*

The outdoor human comfort calculated in the "bocce court" presents the same behaviour as in the other case study: the reduction of the wind speed in the outdoor environment affects the thermal balance of the pedestrian, by reducing the comfortable hours (see Fig. 5). In this case study, the outdoor human comfort is largely impacted during the 21st of June, when the wind speed will be drastically decreased, passing from 1 m/s in average during the daytime, to 0.01 m/s in average for the same period of the day. During the selected day, the pedestrian analysed with the weather data provided by Meteonorm will face just three hours of hot thermal sensation (from 13 to 15 hours) and a warm thermal sensation from 10 to 14 and from 16 to 17 hours. On the contrary the same pedestrian by using the wind profile calculated by CIM, will face a hot thermal sensation from 10 in the morning to 17 in the afternoon. The parameter mostly affected by the wind speed reduction is the sensible heat lost by convection: during the 21st of June it changes from 49 W·m^2 (weather data provided by Meteonorm) to 19 W·m^2 (weather data provided by CIM). By comparing the two locations in the EPFL, a pedestrian located in the square near the Swiss Tech will face during more hours a warm and hot thermal sensation, compared to the bocce court, by using the wind profile provided by Meteonorm. This behaviour varies if using the CIM profile: the wind speed drastically decreases in the bocce court (because of the density of the district) and consequently the discomfort hours are higher in this location compared to the other one.

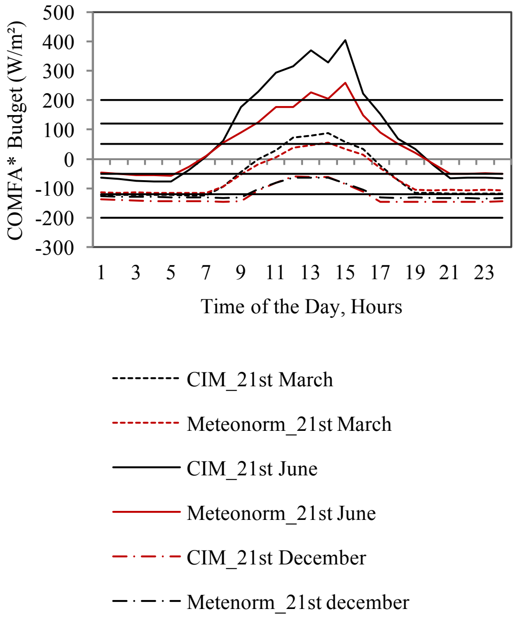

Fig. 5: COMFA energy budget for the bocce court, during the 21st of March, 21st of June and 21st of December. Comparison between weather data provided by Meteonorm (Red) and calculated by CIM (Black).*

5 SUMMARY AND CONCLUSION

This paper describes a new methodology to quantify the impact of the wind speed in the outdoor human comfort, by the use of the Canopy Interface Model, and the COMfort FormulA. In this study, a Canopy Interface Model was used to calculate high-resolution meteorological profiles (every 3 m). The wind speed calculated at 1.5m was then used as an input for the computation of the comfort index.

It was shown that when working in an urban setup, it is necessary to take into account the impact of buildings on the wind patterns, as they are significantly influenced (for ex. a reduction of 80% for the 21st June at midday).

The COMFA* budget varies if using the CIM wind model or the data provided by Meteonorm, by varying the urban density. The example of the bocce court shows an important increase of the warm and hot thermal sensation by using the CIM wind profile, as compared to the Meteonorm one. The human thermal way of exchange that varies the most is the sensible heat lost by convection, that changes from 49 W·m^2 (weather data provided by Meteonorm) to 19 W·m^2 (weather data provided by CIM).

In future studies, we will also look into the impact of the thermal stratification on the temperature profiles in an urban canopy and how this can influence the COMFA* budget.

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