Impact of evapotranspiration on the local microclimate

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Abstract. Climate change is having and will have drastic consequences for high density populated areas such as cities. There is thus a need to develop more tools to evaluate new strategies for adaptation to and mitigation of changing temperatures. Additional functionalities were integrated in the urban energy modelling tool CitySim to include an evapotranspiration process and to integrate low rise vegetation as well as trees. In the process, the Canopy Interface Model (CIM) – previously coupled with CitySim – was further developed to integrate the evapotranspiration process and to analyse its impact on the local microclimate. Evapotranspiration as well as the surface temperature are computed in CitySim and the values are then used as boundary conditions in CIM to calculate the vertical profiles of wind speed, temperature and humidity. Using the campus of the EPFL in Lausanne, Switzerland as a case study, it was demonstrated that the ground evaporative cooling can be an effective mitigation measure for decreasing locally the urban heat island intensity. In future studies, other strategies such as reflective asphalt, will be combined with the evaporative cooling strategies, to determine the most effective action measures that could be easily implemented.

1. Introduction
The current climate change will have a significant impact on urban areas in particular with the expected increase in heat waves[1]. To avoid or to at least decrease the negative side effects of the future temperature increase, urban areas need to decrease their environmental footprint while at the same time designing more liveable urban spaces. There is thus a need for more easy-to-use and practical tools to evaluate new strategies for adaptation and mitigation of climate change.

Greenings play a major role in reducing the urban heat island effect [2], but due to the diverse functions hosted by cities space where greening can be designed are limited. Consequently, it is essential to rethink city design, adopting a bioclimatic approach to be able to increasingly integrate greening design within the urban borders and thus positively face the extreme environmental conditions. Hybrid artificial surfaces should be defined, looking for anthropic functionalities, as well as natural biologic systems, to imitate the cooling potential of natural surfaces. To evaluate the potential of evapotranspiration at the urban scale, tools should be able to account for the impact of such strategies on the local meteorological variables.

In this context, additional functionalities were integrated in the urban modelling tool CitySim to include an evapotranspiration process and to integrate low-rise vegetation as well as trees [3,4]. However, there was not link to the urban climate and hence a lack of feedback on the local climatic variables. The Canopy Interface Model (CIM) [5], a urban climate model that has previously been
coupled with CitySim [6] was further developed to integrate the evapotranspiration process and to analyse its impact on the local microclimate.

2. Methodology
2.1. Integration of the evapotranspiration process in CIM
Coccolo et al., [3] developed a methodology to account for the evapotranspiration process in the urban simulation tool CitySim [7]. Evapotranspiration as well as the surface temperature are computed in CitySim and the values are then used as boundary conditions in CIM to calculate the vertical profiles of the wind speed, temperature and humidity, as presented in Figure 1.

![Figure 1: Schematic representation of the evaporative process in the coupling of CIM-CitySim](image)

CIM is a 1D column model that uses Navier-Stokes reduced to one dimension [5]. The tool was developed to provide a high resolution vertical profile of meteorological variables in particular for the wind, the air temperature or the humidity with the computation of fluxes $F_{q_i}$, as expressed by Equation 1, for humidity:

$$F_{q_i}^H = - \left[ \frac{k}{\ln \left( \frac{\Delta z}{z_{0,h}} \right)} \right]^2 g_h \left( \frac{\Delta z}{z_{0,h}} , Ri_B \right) |U_j| \Delta w_{z_{0,h}}^H \frac{\phi_h}{\phi}$$

(1)

where $k$ is the von Kármán constant, $\Delta w$ is the difference between the water content at the ground surface (taken to be equal to the evapotranspiration computed by CitySim at a height of $z_{0,h}$ - the aerodynamic roughness length (0.05 m)) and the water content at the centre of the cell in the column, $z_{0,h}$ is the roughness length and $g_h$ is the Louis function [8] and is function of the bulk Richardson $Ri_B$. $\phi_h$ is the total horizontal surface of the urban obstacles and $\phi$ the free volume porosity at each level. More details can be found in [5].

The water content at the surface (here the ground) is calculated by CitySim. CitySim provides as output an evapotranspiration rate (i.e. per unit area per hour). There is hence a need to transform the water content obtained from CitySim in terms of water content that can be used in CIM for the computation of the fluxes. The water content, $w_{cim,ground}$, at the ground surface (coming from the evapotranspiration computed in CitySim, $w_{citysim}$) is given as:

$$w_{cim,ground} = \frac{w_{citysim} \rho}{1000}$$

(2)

where $\rho$ is the water density (997 kg/m$^3$). The water content, $w_{cim}$, at each level of the canopy is obtained using:

$$w_{cim} = \frac{RH \cdot p_{sat}}{100}$$

(3)

where $RH$ is the relative humidity from the Meteonorm file and the saturated vapour pressure, $p_{sat}$, is calculated using:

$$p_{sat} = 611 \cdot 10^{\frac{7.5 \cdot \theta}{237.3 + \theta}}$$

(4)
2.2. Experimental setup
The vertical evaporative strategies are evaluated with a series of sensitivity studies were conducted on the EPFL campus in Lausanne (Switzerland), to illustrate the impact of the ground surface properties on the surface temperature and on the relative humidity. Several ground coverages were designed, to improve the cooling potential of the soil:

Table 1: Case studies for the ground used for the analysis.

| Artificial ground          |
|----------------------------|
| Grass, k\textit{factor}=0.3 |
| Grass, k\textit{factor}=0.7 |
| Water                      |
| Evaporative ground, shortwave reflectance=0.2 |
| Evaporative ground, shortwave reflectance=0.7 |

A first simulation is run with an idealized case, with a building and an asphalt ground surface. The properties of the ground surface are modified to evaluate the impact of different cooling strategies. Second, a watered surface (such as a pond) is simulated (see Erreur ! Source du renvoi introuvable.). Third, grass with a k-factor (an index relating to the water content) of 0.3 and 0.7 is implemented. Finally, evaporative grounds (composed of a double layer with one layer presenting a shortwave reflectance of 0.2 and 0.7, and another layer with water flowing) are tested (see Figure 1).

3. Results and Discussions
Simulations were performed for a full typical year with climatic data from Meteonorm [9]. A first set of simulations was first performed in CitySim to obtain the boundary conditions (surface temperatures and evapotranspiration from the ground). The first two scenarios were performed with a ground surface covered with grass with (\textit{kfactor} of 0.7) and without the evapotranspiration to evaluate the impact in the urban canopy. The output from CitySim was then used as boundary conditions for CIM.

Figure shows the vertical profile of the relative humidity as well as the air temperature at 09.00 and 14.00 during a summer day. From Figure , it can be highlighted that there are significant variations along the vertical axis for the relative humidity. It is evident that the addition of the water source close to the ground considerably increases the water content in the first level of the canopy model. Due to the diffusion process in CIM the mixing then changes the water content over the whole column. In particular, the relative humidity increases from 10% very close to the ground to 20% at 09.00 (and from 6% to 20% at 14.00). In the top most layer, the differences are further exacerbated with the relative humidity at 64% in the scenario without evapotranspiration to 81% in the case with at 09.00 (and from 39% to 58% at 14.00).

It can also be noted that the air temperature is significantly reduced close to the ground surface and throughout the column by approximately 10°C in the morning and by 20°C in the afternoon. The effect of the evapotranspiration effect, although occurring at the ground surface, can be transported along the vertical axis and hence change the microclimatic conditions prevailing in the urban canyon.
Figure 2: Vertical profiles of the air temperature (°C) and the relative humidity (%) with and without the evapotranspiration process during a summer day.

Such strategies can thus provide a cooling effect that would be beneficial for the whole urban canopy. To understand the impact of more easily integrated evaporative cooling strategies on the ground, the ground is designed as explained in Section 2.2. Yearly annual simulations were performed for each of the strategies described and the annual surface temperatures are given in Error! Source du renvoi introuvable..

Table 2: Annual surface temperatures for different scenarios

| Average Surface Temperature | Annual surface temperature (°C) | Summer surface temperature (°C) | Spring surface temperature (°C) | Autumn surface temperature (°C) |
|----------------------------|-------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Artificial ground          | 17.4                          | 30.1                            | 23.8                            | 10.3                            |
| Grass, 0.3                 | 13.7                          | 24.0                            | 18.2                            | 8.7                             |
| Grass, 0.7                 | 12.3                          | 21.8                            | 16.0                            | 8.0                             |
| Water                      | 9.7                           | 22.7                            | 14.2                            | 4.8                             |
| Evaporative ground, SW=0.2 | 11.2                          | 19.7                            | 14.5                            | 7.8                             |
| Evaporative ground, SW=0.7 | 8.4                           | 16.1                            | 10.8                            | 6.0                             |

It is quite interesting to note that thanks to the proposed strategies, the annual surface temperature decreases, from a maximum of 17.4°C to 8.4°C. It is, nonetheless, important to understand the seasonal variation, as the capacity of this type of ground is to mitigate the urban environmental conditions, by reducing the temperature during both the warm and the cold season. It can however be noted that there is a lesser decrease in temperature during the autumn (-4.3°C) as compared to the summer (-14°C).
Figure 3: Change in the surface temperature with different cooling strategies.

Figure shows the surface temperatures of the selected urban typologies, during three summer days. The maximal surface temperature is the one of the asphalt, reaching up to 70°C during a warm summer day. The elevated temperature of the asphalt was already monitored in several field studies worldwide, underlining the hot temperatures recorded upon this material. For such climatic conditions, 70°C is a maximal value simulated by the tool; the normal surface temperature corresponds to circa 60°C. Similar values for the asphalt surface temperature were obtained in onsite measurements in Japan, where the surface temperature of porous asphalt reached circa 60°C during the daytime [10].

Figure also demonstrates the effectiveness of the cooling strategies proposed for these three summer days. It is interesting to notice that with the proposed evaporative ground, the surface temperature is significantly reduced. By analysing the surface temperature, the shortwave reflectance plays a major role in the cooling potential of the proposed ground. Indeed, by increasing the albedo up to 0.7, its surface temperature decreases down, to 50°C at noon during a sunny summer day. During the nighttime, the surface temperature is similar to the one of the water, flowing under the first layer of the ground covering.

4. Conclusions and Perspectives
Climate change and the urban heat island effect are posing and will pose significant overheating issues for the urban population. Tools able to integrate multiple urban planning strategies and evaluate their impact on building energy consumption and outdoor thermal comfort are needed. It is thus proposed in this study to further extend the current capacities of the CIM-CitySim tool in order to improve the computation of local climatological variables. This paper presents the new micrometeorological model developed within CIM, as well as the first simulations performed in order to optimise the urban environmental conditions in the EPFL campus.

We demonstrated here how we integrated the evaporative process in CIM to produce a high resolution profile of the temperature and humidity. A clear decrease of the air temperature due to evapotranspiration was noted in the urban canyon. We also showed, using multiple urban planning strategies, that there is an obvious decrease in the temperature when considering or including evaporative cooling techniques.

Due to the non-linear physical processes, a wrong design could lead to a decrease of the outdoor thermal comfort, in particular with a rise in the water vapour content, which leads to higher relative
humidity levels. It was finally demonstrated that the ground evaporative cooling can be an effective mitigation measure for decreasing locally the urban heat island intensity at the scale of the campus. This strategy has a nice potential in outdoor convivial spaces but is clearly not adapted to the street, due to the considerable weight of the cars.

In future studies, other strategies such as reflective asphalt (e.g. yellow asphalt), will be combined with evaporative cooling strategies, to determine the most effective action measures that could be easily implemented for the campus.

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References
[1] IPCC 2013 WORKING GROUP I CONTRIBUTION TO THE IPCC FIFTH ASSESSMENT REPORT CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS (Geneva: Intergovernmental Panel on Climate Change)
[2] Lemonsu A, Masson V, Shashua-Bar L, Erell E and Pearlmutter D 2012 Inclusion of vegetation in the Town Energy Balance model for modelling urban green areas Geosci. Model Dev. 5 1377–93
[3] Coccolo S, Kaempf J, Mauree D and Scartezzini J-L 2018 Cooling potential of greening in the urban environment, a step further towards practice Sustainable Cities and Society
[4] Coccolo S 2017 Bioclimatic design of sustainable campuses using advanced optimisation methods Submitted (Ecole Polytechnique Fédérale de Lausanne)
[5] Mauree D, Blond N, Kohler M and Clappier A 2017 On the Coherence in the Boundary Layer: Development of a Canopy Interface Model Front. Earth Sci. 4
[6] Mauree D, Coccolo S, Kaempf J and Scartezzini J-L 2017 Multi-scale modelling to evaluate building energy consumption at the neighbourhood scale PLOS ONE 12 e0183437
[7] Robinson D 2012 Computer Modelling for Sustainable Urban Design: Physical Principles, Methods and Applications (Routledge)
[8] Louis J-F 1979 A parametric model of vertical eddy fluxes in the atmosphere Boundary-Layer Meteorol 17 187–202
[9] Remund J 2008 Quality of Meteonom Version 6.0 Europe 6 389
[10] Higashiyama H, Sano M, Nakanishi F, Takahashi O and Tsukuma S 2016 Field measurements of road surface temperature of several asphalt pavements with temperature rise reducing function Case Studies in Construction Materials 4 73–80