Validation of a Coupled-Scheme Urban Canopy Model and Building Simulator

Miguel Martin, Masdar Institute of Science and Technology (UAE)
Afshin Afshari, Masdar Institute of Science and Technology (UAE)
Peter Armstrong, Masdar Institute of Science and Technology (UAE)
Leslie Norford, Massachusetts Institute of Technology (USA)

ABSTRACT

The Urban Heat Island (UHI) effect plays a significant role in the livability and energy consumption of urban areas. For this reason, building engineers put a lot of effort into seeking new construction and retrofitting strategies to reduce the impact of this phenomenon on thermal comfort in buildings. These strategies could be optimized as soon as we are able to efficiently approximate temperature differences between the top and the interior of an urban area. In this paper, we would like to determine the accuracy that can be reached using an Urban Canopy Model (UCM) interacting with a Building Simulator (BS) for estimating temperatures inside an urban area. To study the Urban Vertical Stratification (UVS) of air temperature differences in Masdar City, we developed a coupled-scheme Resistance-Capacitance (RC) urban canopy model and EnergyPlus (EP) simulator. For model verification, HOBO loggers and weather stations were deployed at Masdar Institute. As first result, we observed that measurements and the coupled-scheme predictions of the most frequent temperature difference between the urban canyon under study and the first level of atmosphere ΔT_{u-a} had a disagreement of 0.28 degrees Celsius. Regarding the average diurnal cycle of ΔT_{u-a}, both model and observation corroborate the fact that ΔT_{u-a} decreases when the sun rises and increases when the sun shines. These outcomes indicate to us that temperature differences between an urban canyon and the first-level of atmosphere can be relatively well approximated in an urban area that does not have high waste heat releases and anthropogenic heat gains.

Introduction

In the literature, a few studies can be found that address the UHI effect in the Gulf region. The study of Charabi and Bakhit (2011) in the region of Muscat (Oman) is certainly among the most advanced analysis of the UHI effect in the Middle-East. Based on measurements of the temperature inside and outside the city, they were able to compute some properties of the UHI effect in an arid environment. For instance, they found that the UHI intensity is globally higher in summer than in winter. In addition, they demonstrated that the average diurnal cycle of the UHI intensity decreases while the sun sets, and increases while the sun shines. As contribution to the understanding of temperature variations in an urban area of the Gulf region, we would like to proceed to an analysis of the *UVS of air temperature differences*[1] in an urban canyon located in

[1] By UVS of temperature differences, we mean the vertical evolution of air temperature differences from the first-level of atmosphere to the surface of the road in an urban canyon (cf. Georgakis, Santamouris, and Kaisarlis 2010).

Masdar City (UAE). In other words, we endeavor measure and estimate temperature differences between an urban canyon and the *first-level of atmosphere*[2] in an arid climate.

The majority of datasets one can access for UHI and UVS studies contain weather data of Central Europe. BUBBLE, CAPITOUL, and UBL/CLU-ESCOMPTE are the most used datasets for validation of urban canopy models. The BUBBLE dataset (cf. Rotach et al. 2005) consists of a huge set of weather measurements at different heights of rural, suburban, and urban areas around the city of Basel (Switzerland). Similar measurements can be obtained for the city of Marseille (France) via the dataset UBL/CLU-ESCOMPTE (cf. Mestayer et al. 2005). The CAPITOUL dataset described in Masson et al. (2008) provides weather data - albeit at lower resolution than the other two - for the city of Toulouse (France). However, these three datasets are located between zones 8a and 9a in the USDA hardiness map (cf. PlantsDB 2011). This means that they enable us to assess the accuracy of an UCM on a restricted region where the average annual extreme minimum temperatures are between -12.2 [^{o}C] and -3.9 [^{o}C]. In Abu Dhabi, the average annual extreme minimum temperatures are estimated between 7.2 [^{o}C] and 10 [^{o}C]. To generate a weather dataset for UCM validation in hot arid environments, several facilities - like a network of 12 HOBO loggers and a group of weather stations - were installed at Masdar Institute.

A comparison between the average diurnal cycle of urban temperatures computed from measurements and the one estimated from the UCM is often provided for demonstrating the accuracy of the model. As example, the TEB model defined in Lemonsu et al. (2004) is validated in such a way. They compared measured temperatures in specific urban canyon of Marseille downtown with the ones simulated by the TEB model (in terms of average diurnal cycle). Using this methodology, they were able to evaluate the improvements achieved from an old version to a new version of the TEB model. In our study, we would like to apply a similar validation protocol on temperature difference between an urban canyon (located in Masdar Institute) and the first level of atmosphere ΔT_{u-a}. In addition to the average diurnal cycle analysis, we also want to compare the frequency distributions of ΔT_{u-a} predicted by measurements and by the UCM.

One of the major contribution in the field of urban canopy models comes from Bueno Unzeta (2010) and Bueno Unzeta et al. (2012). In Bueno Unzeta (2010), an urban canopy model coupled to a building simulator is developed. The general idea behind this coupled-scheme is to make the UCM defined in Masson (2000) interact with the EP building simulator, and vice versa. This new methodology allows us to design UCMs that include detailed building models. After this work, a simplified version of the TEB model is elaborated in Bueno et al. (2012). The aim of this UCM is to model heat transfers between each thermal nodes of an RC model. Because this UCM can easily be formulated as a state-space, the computation of the current temperature of a thermal node can be significantly accelerated by employing numeric simulation tools like Matlab. As extension of these researches, we implemented a technique which aims to estimate the shading effect in an urban canyon using trigonometry on the zenith and azimuth angles of the sun.

To create a scalable and computationally fast UCM for the analysis of the UVS of air temperature differences in Masdar City, we decided to develop a coupled-scheme, that is, an RC model coupled to EP simulator. To validate the coupled model in terms of average diurnal cycle and frequency distribution, we measured temperatures at different heights of an urban canyon located at Masdar Institute using a network of HOBO loggers and a weather station. From the frequency distribution analysis, it turned out that the most frequent ΔT_{u-a} predicted by the model and measurements is only 0.28 degrees Celsius different. On the other side, the average diurnal

[2] The first-level of atmosphere above an urban area is usually computed multiplying by two the average height of buildings (cf. Bueno Unzeta 2010).

cycle study revealed that ΔT_{u-a} is higher during daytime than at night. These results provide us further evidence that UCM developed in Bueno Unzeta (2010) and Bueno et al. (2012) can work reasonably well in arid climates like the one in UAE.

Urban Canopy Model

As we mentioned in the Introduction section, we combined a resistance-capacitance urban canopy model (cf. Bueno et al. 2012) with the EP simulator in order to estimate temperatures inside an urban canyon. In short, we first used the EP simulator for computing wall temperatures, wall convective heat transfer coefficients (CHTCs), waste heat releases, and sky temperatures. After that, all these values were iteratively conveyed to the RC model so as to update the urban canyon temperature and the road surface temperature. In addition to the information sent by the EP simulator, the RC model also required several weather parameters measured at the first-level of atmosphere for updating the canyon and the road temperature. These weather parameters were dry-bulb temperature, air pressure, direct normal radiation, diffuse horizontal radiation, relative humidity, and wind speed. Finally, it is necessary to substitute dry-bulb temperatures, the relative humidity, and wind speeds usually sent to the EP simulator through an EPW file by the ones calculated from the RC model.

In order to avoid running several EP processes at the same time, we assumed that one building – of the urban area under study – is surrounded by four identical buildings. In other words, we approximated ΔT_{u-a} inside a north, south, west, and east canyon taking in account that the properties of a given wall are equal to all walls with same sun exposure.

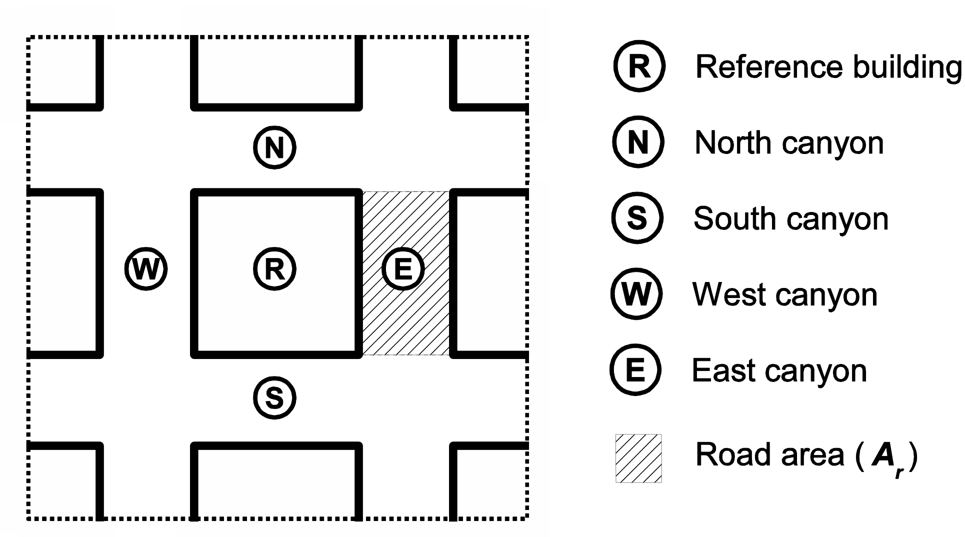

Figure 1. Topography of the urban canopy model.

To define the way we wanted to iteratively update the urban temperature T_u and the road temperature T_r, we derived two differential equations from Bueno et al. (2012):

$$C_u \frac{dT_u}{dt} = A_u \frac{T_a - T_u}{R_{a,u}} + A_w \frac{\bar{T}_{wl} - T_u}{R_{wl,u}} + A_w \frac{\bar{T}_{wr} - T_u}{R_{wr,u}} + A_u \frac{T_r - T_u}{R_{r,u}} + A_u \frac{T_{sky} - T_u}{R_{sky,u}} + \sum Q \quad (1)$$

$$C_r \frac{dT_r}{dt} = A_r \frac{T_u - T_r}{R_{r,u}} + A_r \frac{T_{sky} - T_r}{R_{sky,r}} + A_r Q_r^* \quad (2)$$

where $\sum Q = Q_{waste} + Q_{antro}$, $A_u = A_r$, and $\bar{T}_{wl}$ and $\bar{T}_{wr}$ are average temperatures computed over each wall of the left and right façade, respectively. It is important to keep in mind that all thermal resistance $R_{x,y}$ are time varying.

From the differential equations (1) and (2), we formulated a state-space $\nabla\boldsymbol{T} = \boldsymbol{AT} + \boldsymbol{BU}$ in which $\nabla\boldsymbol{T} = \left[\frac{dT_u}{dt}, \frac{dT_r}{dt}\right]$, $\boldsymbol{T} = [T_u, T_r]$, and $\boldsymbol{U} = \left[T_a, \bar{T}_{wl}, \bar{T}_{wr}, T_{sky}, \sum Q, Q_r^*\right]$. Employing the Euler backward method for numerical estimation of a first derivative, we were able to iteratively update the vector $\boldsymbol{T}$ as following:

$$\boldsymbol{T}_{t+1} = (I - dt\boldsymbol{A}_{t+1})^{-1}(\boldsymbol{T}_t + dt\boldsymbol{B}_{t+1}\boldsymbol{U}_{t+1}) \quad (3)$$

In the above equation, $\boldsymbol{A}_{t+1}$, $\boldsymbol{B}_{t+1}$ and $\boldsymbol{U}_{t+1}$ are the state-space matrix, the input matrix, and the input vector, respectively, computed from weather parameters at time $t + 1$. The sampling rate dt was set to 1800 [s].

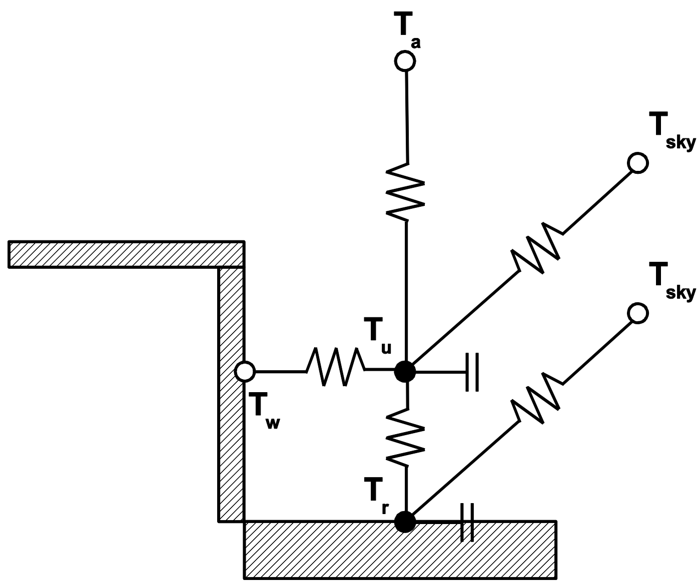

Figure 2. Resistance-Capacitance urban canopy model.

Solar Radiation Incident on Road Surface

According to Masson (2000), solar radiations on the road can be expressed as linear combination of road direct solar radiations Q_r^{Dir}, road diffuse solar radiations Q_r^{Diff}, and the sum of solar reflexions incident on road M_r (Masson 2000, Eq. 16), i.e:

$$Q_r^* = (1 - \varepsilon_r)Q_r^{Dir} + (1 - \varepsilon_r)Q_r^{Diff} + (1 - \varepsilon_r)(1 - \varphi_r)\, M_r \quad (4)$$

The sky-view factor of the road φ_r is defined as:

$$\varphi_r = \sqrt{(z_b/w_r)^2 + 1} - z_b/w_r \quad (5)$$

From Eq. 5.26 in Bueno Unzeta (2010), we evaluated road direct solar radiations Q_r^{Dir} as shown below:

$$Q_r^{Dir} = Q^{Dir}\left(1 - \frac{A_r^*}{A_r}\right) \tag{6}$$

In the same logic, we calculated wall direct solar radiations as:

$$Q_w^{Dir} = Q^{Dir}\left(1 - \frac{A_w^*}{A_w}\right) \tag{7}$$

Both shaded areas A_r^* and A_w^* vary over time as a function of the zenith and azimuth angles of the sun. Depending on the value of these two parameters, we assumed that the road shaded area A_r^* can be approximated either as a trapezoid or as a triangle. On the other hand, the wall shaded area A_w^* was always estimated as a rectangle.

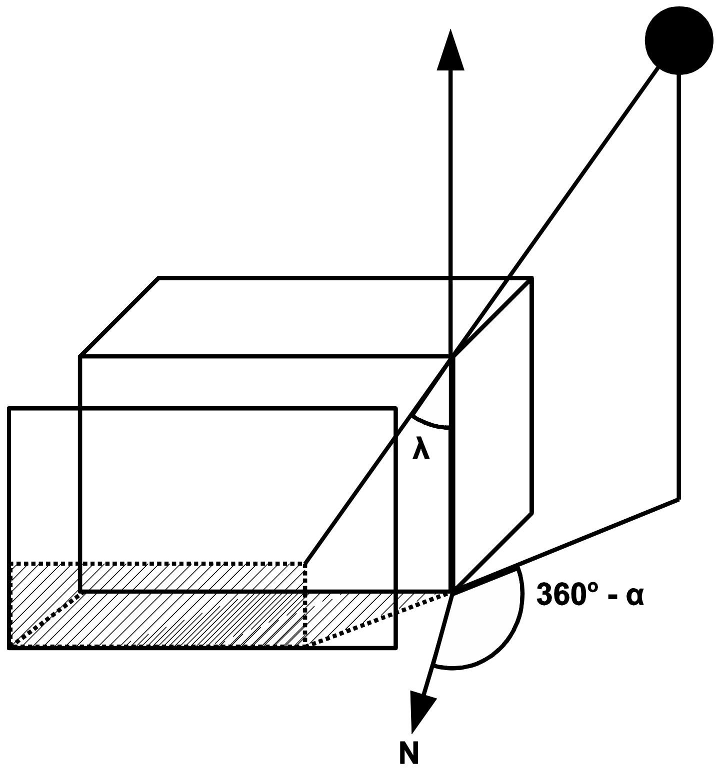

Figure 3. Shading effect on the urban canyon.

In accordance with Bueno Unzeta (2010), we simply evaluated both the road and the wall diffuse solar radiations as:

$$Q_r^{Diff} = Q^{Diff}\varphi_r \tag{8}$$

$$Q_w^{Diff} = Q^{Diff}\varphi_w \tag{9}$$

The sky-view of the wall φ_w is simply expressed as:

$$\varphi_w = \frac{1}{2}\left[z_b/w_r + 1 - \sqrt{(z_b/w_r)^2 + 1}\right]/(z_b/w_r) \tag{10}$$

Thermal Resistances

As stated at the beginning of section Urban Canopy Model, we used the EP simulator with the aim of getting CHTCs for the left and the right façades. Left and right CHTCs were employed for the computation of thermal resistances between walls and the urban canyon, i.e:

$$R_{wl,u} = \left(\bar{h}_{wl}\right)^{-1} \tag{11}$$

$$R_{wr,u} = \left(\bar{h}_{wr}\right)^{-1} \tag{12}$$

As in the case of wall surface temperatures, left and right CHTCs were averaged over each wall of the left and right façade.

Based on Eq. 23 in Masson (2000), we defined the following expression for the thermal resistance computation between the road and the canyon:

$$R_{r,u} = \left(11.8 + 4.2U_{eff}\right)^{-1} \tag{13}$$

where $U_{eff} = \sqrt{U_{can}^2 + u_*^2}$ represents the effective wind speed in the urban canyon.

According to Bueno Unzeta (2010), the thermal resistance between the first-level of atmosphere and the urban canyon can be approximated using the following expression:

$$R_{a,u} = (c_u \rho_u U_{ex})^{-1} \tag{14}$$

in which $U_{ex} = 1.35 C_d U_a$ is the exchange velocity between the first-level of atmosphere and the urban canyon (Bueno Unzeta 2012). We assumed $C_d = a^2 F_m$ using the function F_m defined in Mascart et al. (1995).

The thermal resistance between any surface and the sky was defined based on radiative heat transfer coefficients (RHTCs) formulated in Bueno Unzeta (2012), i.e:

$$R_{sky,u} = \left(4\varepsilon_u \sigma \left[\frac{T_{sky} + T_u}{2}\right]^3\right)^{-1} \tag{15}$$

$$R_{sky,r} = \left(4(1-\varepsilon_u)\varepsilon_r \varphi_r \sigma \left[\frac{T_{sky} + T_r}{2}\right]^3\right)^{-1} \tag{16}$$

where $\sigma = 5.67 \cdot 10^{-8}$ [W/m^2-K^4]. The emissivity of the urban canyon air mass ε_u can be estimated using the Eq. D.3 in Bueno Unzeta (2012).

Heat Capacities

Heat capacities of the road and the urban canyon were computed by applying the following expressions:

$$C_r = V_r c_r \rho_r \tag{17}$$

$$C_u = V_u c_u \rho_u \tag{18}$$

where c_u and ρ_u are the heat capacity and the density, respectively, of moist air.

Validation Model

For the purpose of validating our coupled-scheme RC model and EP simulator, we decided to model the Wave Block canyon in which eight HOBO loggers were installed. This urban canyon is located in Masdar Institute (i.e 24.43^o latitude, 54.61^o longitude, and 27 [m] altitude). The main reason why we chose this urban canyon instead of another at Masdar Institute is because its remoteness from the wind tower. The wind tower is a facility that might be the source of turbulences, and, therefore, might cause a strong thermal instability in the urban canyon.

The Wave Block canyon is situated in an area with low anthropogenic heat gains and low waste heat releases. There is neither car traffic nor strong human activity on the street of this urban canyon. The HVAC system delivering cooling air to Masdar Institute's buildings is located at the PRT station (i.e out of the campus). For all these reasons, we assumed that the anthropogenic heat gains and the waste heat releases are equals to zero.

Residential Building Model

The Wave Block canyon is connected to two different types of buildings: one residential building and one laboratory building. The residential buildings are 4-floor buildings made up of walls with a high thermal resistance and a small glazing ratio. These buildings were built in the aim of accommodating Masdar students, and limiting the energy consumption due to the use of air-conditioning. On the other side, the laboratory buildings were made for including research activities. One of its specificity is the metallic envelop covering the building. Thermal and glazing characteristics of these buildings are relatively close to residential buildings.

As mentioned in the Urban Canopy Model section, the coupled-scheme considers that all surrounding buildings of the reference building are identical in dimension and composition. Due to some issues in estimating the emissivity of laboratory buildings' walls, we made the assumption that the Wave Block canyon is only connected by residential buildings.

	Settings
Road width	8 m
Road depth	0.75 m
Road volumetric heat capacity	1.4 MJ/m^{3}K
Road albedo	0.4
Building height	14 m
Building length	20 m
Building width	60 m
Building orientation	37^o
Wall albedo	0.2
Wall U-value	0.25 W/m^{2}K
Window U-value	2 W/m^{2}K

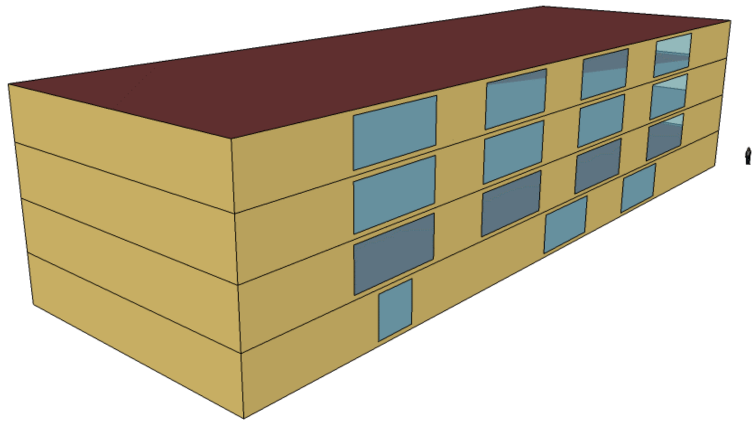

Figure 4. Building model for residential buildings at Masdar Institute.

Validation Data Set

To evaluate the accuracy with which the coupled-scheme estimates ΔT_{u-a} in the Wave Block canyon, we computed temperature differences $\Delta T_{u-a} = \bar{T}_{HOBO} - T_{WTWS}$ between the average temperatures measured by two HOBO loggers $\bar{T}_{HOBO}$ (i.e HOBO WA1:01 and HOBO WA1:05) and the temperatures recorded by the Wind Tower Weather Station (WTWS) T_{WTWS}. First of all, we took in account only two HOBO loggers for calculating the temperatures inside the Wave Block canyon because of the location where they were installed. Apart HOBO WA1:01 and HOBO WA1:05, all other HOBO loggers were attached behind a balcony wall of the residential building. Consequently, HOBO WA1:01 and HOBO WA1:05 were the only measuring devices directly connected to the air volume of the Wave Block canyon at an elevation of 3 [m]. Finally, we made the decision to consider the weather station located on the wind tower as measurement point for temperatures at the top of the Wave Block canyon. This weather station is certainly the closest dry-bulb air temperature recording device to the first-level of atmosphere situated over Masdar Institute.

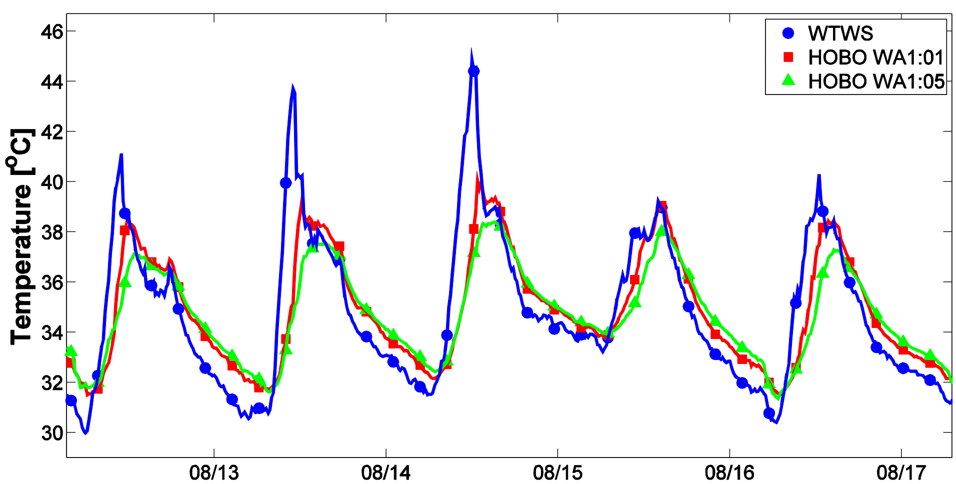

Figure 5. Portion of HOBO loggers and WTWS temperatures from August 4th 2011 at 1:00 am to October 3rd 2011 at 12:00 am UTC + 4.

Results

Before estimating ΔT_{u-a} with the coupled-scheme, we evaluated the frequency distribution of ΔT_{u-a} computed from measurements using a histogram estimator of 100 bins. From this computation, a frequency distribution with a clear peak at 0.86 [°C] is seen in Figure 6.

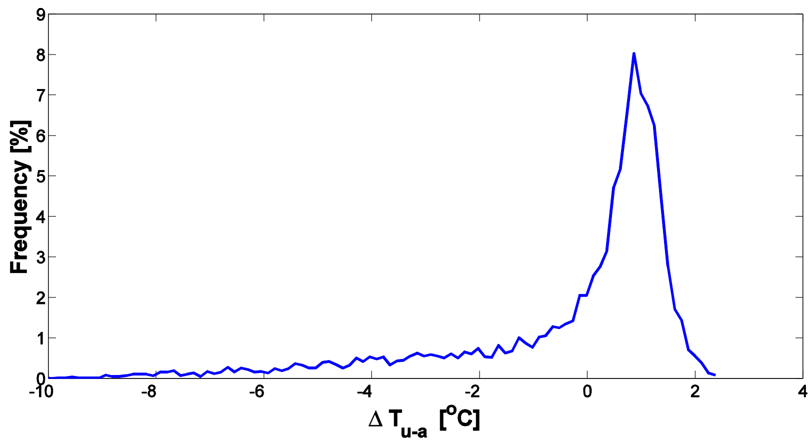

Figure 6. Frequency distribution of ΔT_{u-a} computed from measurements between August 4th 2011 at 1:00 am and October 3rd 2011 at 12:00 am UTC + 4.

To estimate the frequency distribution of ΔT_{u-a} by our model, we first ran the coupled-scheme with an EPW file created with measurements coming from the WTWS and the Masdar Weather Station (MWS). The WTWS was used for measuring dry-bulb temperature, relative humidity, atmospheric pressure, wind speed, and wind direction above the Wave block canyon. To record direct normal radiations and diffuse horizontal radiations reaching the Wave block canyon, we employed the MWS located in the surrounding rural area about 1 [km] south of Masdar Institute. As estimation of ΔT_{u-a}, we took $\Delta T_{u-a} = T_u - T_{WTWS}$ between the estimated temperatures inside the Wave Block by the coupled-scheme T_u and ambient temperatures stored inside the EPW file T_a. At the end, we calculated the frequency distribution of ΔT_{u-a} with the same non-parametric estimator.

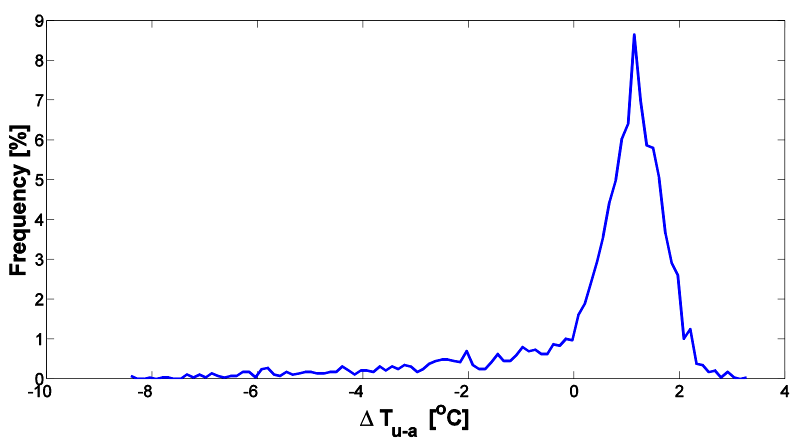

Figure 7. Frequency distribution of ΔT_{u-a} computed from the coupled-scheme between August 4th 2011 at 1:00 am and October 3rd 2011 at 12:00 am UTC + 4.

As frequency distribution of ΔT_{u-a} computed from the coupled-scheme (cf. Figure 7), we got a distribution similar to the one computed from measurements (cf. Figure 6) with a peak located at 1.14 [^{o}C]. That is to say, the most frequent ΔT_{u-a} predicted by the coupled-scheme was 0.28 [^{o}C] different from the one forecasted by measurements.

In addition to the frequency distribution analysis, we were interested in comparing the average diurnal cycle of ΔT_{u-a} computed from measurements with the one computed from the coupled-scheme (cf. Figure 8). Both of them seemed to decrease when the sun rises and to increase after noon.

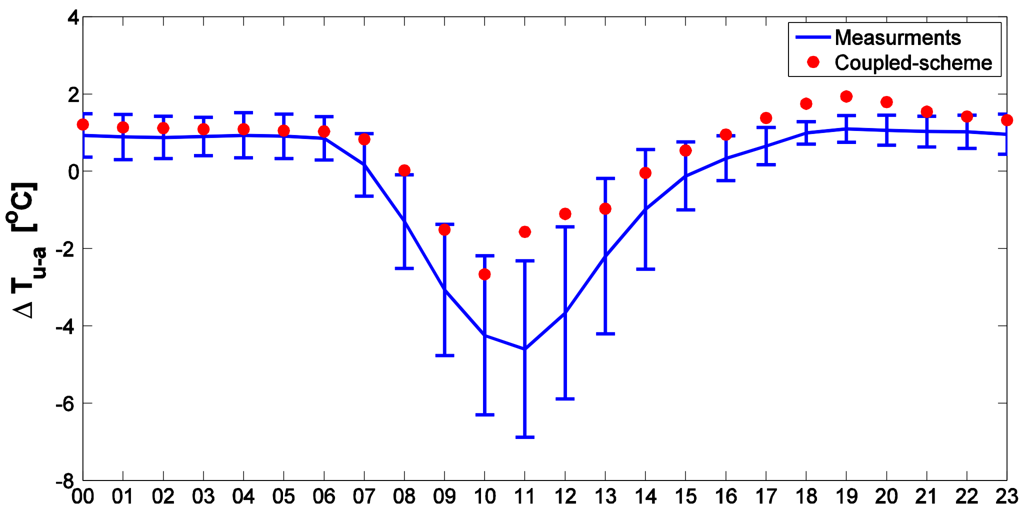

Figure 8. Average diurnal cycle of ΔT_{u-a} computed from measurements and the coupled-scheme between August 4th 2011 at 1:00 am and October 3rd 2011 at 12:00 am UTC + 4.

Conclusion

In this paper, we introduced a coupled-scheme RC model and EP simulator which was used for estimating temperature difference between the Wave Block urban canyon and the first level of atmosphere ΔT_{u-a} in an urban canyon located at Masdar Institute. To evaluate the accuracy of the coupled-scheme, we measured ΔT_{u-a} of a specific canyon employing HOBO loggers and a weather station.

In terms of frequency distribution and average diurnal cycle of ΔT_{u-a}, the behaviors predicted made by the coupled-scheme are close to the ones concluded by measurements. Both measurements and the coupled-scheme agree that ΔT_{u-a} in the Wave Block canyon attains its peak value between 0.8 and 1.2 degrees Celsius, and reaches its daily minimum value between 10:00 am and 12:00 am.

These results demonstrate that the use of a coupled-scheme is efficient for analyzing the UVS of air temperature differences in an arid climate. However, temperatures of the urban canyon we considered for validating the coupled-scheme are not strongly influenced by waste heat releases coming from buildings, and anthropogenic heat gains coming from streets. In the future, it would be interesting to increase the resolution of the UVS of air temperature differences analyzed by our coupled-scheme, and to test it on an urban area in Abu Dhabi downtown with appropriate measurements for validation.

Nomenclature

Symbol	*Quantity*	*[SI unit]*
α	Azimuth angle of the sun	[Deg]
λ	Zenith angle of the sun	[Deg]
φ_x	Sky view factor of surface x	[-]
ρ_x	Density of x	[kg/m^3]
ε_x	Emissivity of x	[-]
A_x^*	Shaded area of x	[m^2]
A_x	Area of x	[m^2]
C_d	Drag coefficient	[-]
C_x	Heat capacity of x	[J/K]
c_x	Specific heat capacity of x	[J/kg-K]
h_x	Convective heat transfer coefficient of surface x	[W/m-K]
Q_x^*	Solar radiations on surface x	[W/m^2]
Q_x^{Dir}	Direct solar radiations on surface x	[W/m^2]
Q_x^{Diff}	Diffuse solar radiations on surface x	[W/m^2]
Q_x	Heat or heat flux x	[W] or [W/m^2]
$R_{x,y}$	Thermal resistance between x and y	[m^2-K/W]
T_x	Temperature of x	[K] or [^oC]
ΔT_{x-y}	Temperature difference between x and y	[^oC]
u_*	Friction velocity	[m/s]
U_x	Wind speed of x	[m/s]
U_{can}	Horizontal wind speed inside a urban canyon	[m/s]
V_x	Volume of x	[m^3]
w_x	Width of x	[m]
z_x	Height of x	[m]

Subscripts

Symbol	*Meaning*
a	First-level of atmosphere
b	Building
r	Road
sky	Sky
u	Urban canyon
w	Wall
wl	Left wall
wr	Right wall

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