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Numerical modelling evaluation for the microclimate of an outdoor urban form in Cairo, Egypt

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Abstract In order to achieve outdoor thermal comfort it is necessary to understand the interactions between the prevailing climate, the urban form and roughness. The near surface boundary layer is directly influenced by local irradiative and convective exchange processes due to the presence of a variety of different surfaces, sheltering elements and obstacles to air flow leading to distinctive micro-scale climates. The paper presents a micro-scale numerical model for an outdoor urban form for a hot summer’s day in Al-Muizz street located at the Islamic quarter of Cairo, where a few studies have attempted to study these conditions in vernacular settings in hot arid areas where the continuously evolving urban patterns and shaded environments were perceived to produce more pedestrian friendly outdoor environments. In situ measurements are used to validate the ENVI-met results which showed an overall agreement with the observed ones, representing adequate mean radiant temperature (Tmrt) which is one of the most important meteorological parameters governing human energy balance and has therefore a strong influence on thermal sensation of the pedestrians using the open public spaces and generating a micro-climatic map as an initial step in addressing the urgent need for a modelling platform accessible to urban designers, architects, and decision makers towards sustainable urban forms.

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Introduction

The 4th IPCC Assessment Report (2011) indicated that Africa is warming faster than the global average, and this is likely to continue. This warming is greatest over the interior of semi-arid margins of the Sahara and central southern Africa [1]. This was compiled with the ACED (2004) [2] studies that reported changes in area averaged temperature and precipitation over Egypt which was assessed based upon a dozen recent GCMs (General Circulation Models) using a new version of...
MAGICC/SCENGEN. All climate models estimated a steady increase in temperatures for Egypt, with little intermodal variance. That mostly attributes to the large fractions of the Earth’s surface modified by human changes, particularly in cities through a large number and variety of constructions, leading to a changed energy balance of the surface and to the formation of local, man-modified microclimates.

This caused the urban areas to warm up much faster and cool down much slower than their rural surroundings due to their sealed surfaces. This provokes the creation of warmer zones in urban regions. This is known as urban heat island phenomenon and represents a feedback of the atmospheric variables on the use of the ground and the degree of soil sealing. This phenomenon and the effect it causes on air temperature as a result of urbanisation are now well documented in numerous studies [3–5] stating that the world’s average air temperature has risen between 0.3 and 0.6 °C since the late 19th century [6]. As a result, the urban microclimate starts to gain increasing attention during urban design and spatial planning [7], starting with the study and description of microclimate processes, and then focusing on microclimate research in relation to outdoor thermal comfort contributions such as those of Oke et al. [37], Bosselmann et al., Katzschner, Moriwaki and Kanda, Katzschner et al. (2004) and Stathopoulos [8–12] which were interesting for urban design because they addressed factors that can be changed through urban design interventions. As it is well explained in the practice-oriented literature that Urban microclimate depends on the type of city in terms of size, geographical location, population size and density, and land use as well as the street design features such as height of buildings, street widths and orientation, subdivision of the building lots, etc., the urban design of each neighbourhood in a city creates its own particular local climate [13], where with well-defined planning measures the micro climate can be improved or negative effects can be mitigated [14,15].

Givoni et al. [16] highlighted the designers’ need for urban climatic predicting tools to evaluate the effect of urban microclimatic changes on outdoor human thermal comfort and these tools need to provide the ability to process detailed environmental information according to time and location variations and to generate analytical results to reveal the relationship amongst the microclimatic environment, outdoor urban design and thermal comfort. In this study the microclimatic effects of an urban site located within the Islamic Quarter of Cairo are numerically assessed using the numerical model ENVI-met 3.1.

The study context

The Cairo zone lies between latitude 26°50’ N and 30°45’ N. In the middle of that area lies Al-Muizz street as shown in Fig. 1, which divides Islamic Cairo down the middle. The street has the greatest concentration of Islamic architectural treasures in the world and offers a vivid example of how life in Islamic Cairo might have looked like thousands of years ago. In the late 90’s the UNESCO recognising that Al-Muizz and its surroundings hold great historical and cultural value declared Islamic Cairo a protected world heritage site. A massive restoration project was commissioned by the Egyptian government to restore Al-Muizz street and its surroundings, transforming the street into an open-air museum. The first part of the street was fully restored and was opened to the public in Early 2010. The second part of the street is yet to undergo restoration work.

The case study – according to Koppen classification – is classified within group B and sub group BWh – arid or desert
with hot climate [17], which is characterised by sparse rainfall and a vast daily temperature range.

Methodology

Micrometeorology site measurements

Based on 30 years of data from the WMO Station No. 623660 records at Cairo international airport June and July are considered the hottest months. The data also emphasised the homogeneity of the climatic condition in the summer of Cairo as shown in Fig. 2, i.e. hot, sunny and cloudless. Therefore, meteorological measurements were carried out between 26th June and 2nd July 2012 representing one week pattern of Cairo extreme hot summer. As stated in ASHRAE fundamental handbook (2009) [18] the four main parameters were measured including air temperature, relative humidity, solar radiation and wind speed, in addition to globe temperature which is used to calculate the mean radiant temperature (Tmrt).

Numerical simulation

The model simulations have been carried out with the three-dimensional non-hydrostatic climate model ENVI-met version 3.1 [19]. ENVI-met is a computer programme that predicts micro climate in urban areas [20]. They describe it as “a three dimensional microclimate model designed to simulate the surface-plant-air interactions in urban environment with a typical resolution of 0.5–10 m in space and 10 s in time. ENVI-met is a prognostic model based on the fundamental laws of fluid dynamics and thermodynamics. The model includes the simulation of flow around and between buildings, exchanges processes of heat and vapours at the ground surface and at walls, turbulence, exchange at vegetation and vegetation parameters, bioclimatology, particle dispersion.” (ENVI-met website: www.envi-met.com).

ENVI-met has almost all the algorithms of a CFD package such as the model navier stoke equation for wind flow, E-z atmospheric flow turbulence equations, energy and momentum equation and boundary condition parameters. Yet it is more developed than a specialist CFD package as it simulates the soil/plant/surface/air relation by applying a numerical model for each [21]. It almost has the complete ability to simulate built environments from the microclimate to local climate scale at any location, regardless of overestimation due to uncalculating soil heat storage [22], global radiation overestimation by day and underestimation of nocturnal by night [23]. Moreover, ENVI-met’s combination of bio-meteorological output provides an in-depth understanding of climate urban canopy layer [24] and better assessment for the outdoor comfort levels based on human biometeorology [25].

For the model simulations, Al-Muizz alley has been transformed into a model grid with the dimension 30 \times 140 \times 30 with a resolution of 1 m \times 1 m \times 3 m for the renovated part. Note that the model area is rotated 15° out of grid north. Table 1 shows the simulation input data for the 1st of July 2012 which is the extreme summer day for Cairo. The snapshot receptor was located at the same spots of the measurement campaign to record $T_a$, RH, V, solar radiation and Globe temperature at 1.2 m above the ground level. Outputs were then compared with the local climate scale averaged records for the same parameters observed from the site measurement.

Table 1 Main input data used for ENVI-met.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_a$, air dry bulb temperature</td>
<td>308°C</td>
</tr>
<tr>
<td>RH, relative humidity</td>
<td>59%</td>
</tr>
<tr>
<td>V, wind speed soil temperature</td>
<td>3.5 m/s at 10 m height 302 at (0-0.5 m) and 299 at (0.5-2m)</td>
</tr>
<tr>
<td>U value walls</td>
<td>1.7</td>
</tr>
<tr>
<td>U value roofs</td>
<td>2.2</td>
</tr>
<tr>
<td>Albedo walls</td>
<td>0.4</td>
</tr>
<tr>
<td>Albedo roofs</td>
<td>0.15</td>
</tr>
</tbody>
</table>

As shown in Fig. 3, the model simulation outputs at 1.2 m (due to the vertical model resolution) are plotted against the data observed at 1.1 m above the ground for the Al-Muizz alley. ENVI-met estimation for the dry air temperature ($T_a$) was in a good approximation with the observed ones. As shown in Fig. 3, the air temperature ($T_a$) for the observed and modelled reached their peak in the afternoon, between 11 a.m. and 3 p.m. with peak value of 37.48 °C observed air temperature against 35.2 °C computed air temperature. The regression analyses between the measured and computed were calculated with correlation coefficient $R^2 = 0.942$ for a linear relationship. Thus, the measured and computed ENVI-met for air temperature is well correlated and considered reliable in presenting the current air temperature condition of Al-Muizz street. Relative humidity in Fig. 4 also showed a good agreement between the RH observed from the site measurement campaign and the RH generated by the ENVI-met, as they reached their maximum in the late morning between 6 am and 10 am where the observed RH was 72% and 50% corresponding to ENVI-met estimation which was 66% and 58%.
Fig. 3 Comparison between the dry air temperature measured and the ENVI-met output.

Mean radiant temperature (Tmrt)

Fig. 5 shows the Tmrt calculated using the 25 mm flat black globe thermometer compared to the Tmrt estimated by ENVI-met. Tmrt summarises all short and long wave radiation fluxes reaching the human body in urban settings. The theory of the globe thermometer has been thoroughly explained by Kuehn et al. [26]. It was originally developed for the indoor application then extended to include the outdoor settings [27]. Simply, if the globe temperature, air temperature and air velocity are known then the Tmrt can be calculated to diminishing the wind factor and the diameter of the globe according to Eq. (1) given by ASHRAE [18] with empirical coefficient recently refined by Thorsson et al. is [28]:

\[
T_{mrt} = \left[ (T_g + 273)^4 + \frac{1.1 \times 10^8 T_g^{0.6}}{a_g D^{0.2}} \times (T_g - T_a) \right]^{1/4} - 273
\]

(1)

where \(T_g\) is the globe temperature (°C), \(V_a\) is air velocity (m/s), \(T_a\) is the air temperature (°C), \(D\) is the globe diameter (mm) (= 152 mm in this study), and \(a_g\) is the globe emissivity (= 0.95 for black-colour globe). The empirically derived parameter \(1.1 \times 10^8\) and the wind exponent \((V_a^{0.6})\) together represent the globe’s mean convection coefficient \((1.1 \times 10^8 V_a^{0.6})\).

ENVI-met is found to represent well the trends of the Tmrt with a calculated correlation coefficient \((R^2)\) during the daytime between the measured and computed equal to 0.916. However, simulated values of Tmrt were underestimated after the sunset in comparison to field data. This may attribute to the decrease in short wave radiation after the sunset as it can go down by 20 °C of the main radiant temperature [28]. Furthermore, the material heat storage is not taken into account during simulation, where the heat stored in the building and transferred through walls and roof is calculated by conducting \(U\)-values, while in real cases, each material has its own thermal properties expressed by thermal admittance \(\mu = (KC) 0.5\) where \((K)\) represents thermal conductivity and \((C)\) represents heat capacity, therefore the lack of heat storage in the ENVI-met leads to an overestimation of the long wave radiation emitted by walls during the daytime and underestimation during the night where no heat can be released after sunset [25, 27].

Radiation map

According to a well literature review, the mean radiant temperature (Tmrt) is one of the most important meteorological parameters governing human energy balance and a key variable in evaluating thermal sensation outdoors under sunny conditions regardless of the comfort index used [29–31]. In this view the models show specific areas with high Tmrt a temperature where action is needed (Fig. 6). And because, the sun and shade are the most predetermined parameters influencing mean radiant temperature [32], it was essential to generate radiation patterns to identify locations with solar energy conversion potential or areas in need of shading due to excessive solar exposure and high Tmrt, which will need to be studied and avoided in the future. The diva for rhino – which is sustainable analysis plugin for the Rhinoceros 3D Nurbs modelling programme – was used to identify locations with solar energy conversion potential or areas in need of shading due to excessive solar exposure through the radiation map developed in Fig. 7. Diva performs a detailed day lighting analysis using Radiance/DAYSIM with thermal load simulations using EnergyPlus within [33] which is a powerful tool that can be used on an urban or building scale.
The creation of new design guidelines based on scientific knowledge has been identified to be very important to close the manifold ‘utility gaps’ [34,35] between science and design practice. To enhance the use of scientific knowledge in design, it is crucial to provide practitioners with easily applicable, ‘pre-processed’ scientific knowledge. In this paper, the application of the ENVI-met averaging tool has been validated through comparing the simulation outputs of different parameters with the in situ measurement outcomes, resulting in an overall acceptable agreement of the model performance. The conclusions of the analysis presented herein are summarised as follows:

1. The results obtained provide some problematic areas (UHI) concerning pedestrian’s thermal comfort even after the restoration project, which need to be studied and avoided in the future. Therefore, in any planning process, or architectural intervention spatial distribution maps for microclimate conditions should be presented before construction.

2. The design of outdoor public spaces without a specific awareness to the microclimate is usually caused by insufficient knowledge about microclimate processes amongst many landscape architects and urban designers [34,36]. And in order to overcome the problem more efforts still have to be made. Easily applicable design guidelines should be generated in order to encourage a better inclusion of microclimate issues in urban space design.

3. Although simulations can be very useful tools for predicting microclimate situations, they are only as precise as their underlying mathematical models and the way these are integrated in the simulations. ENVI-met still has some shortages as mentioned earlier.

Even so, these simulation tools are in constant development and are calibrated to make better predictions. ENVI-met was authorised by The EU-project BUGS (Benefits of Urban Green Spaces) and The Dutch Air Quality Innovation Program (IPL) initiated by the Dutch ministries for Transport, Public Works and Water Management (Rijkswaterstaat) and for Housing, Spatial Planning and Environment (Ministry of VROM). Thus, in the future, it will be increasingly useful to integrate simulations into outdoor space design processes.

**Conflict of interest**

None declared.

**References**


Numerical modelling evaluation for the microclimate


