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Abstract: Urban planning, building design and landscaping can all provide strategies for the urban heat island (UHI) mitigation and directly affect people’s living environment and thermal comfort. In order to better improve the urban microclimate through rational building envelope design and landscaping, an example of a new residential area with 10,000 m² floor area located in Osaka, Japan is examined. The effect of urban green covering (UGC), urban albedo (UA) and urban aspect ratio (UAR) on urban microclimate was investigated with the environmental simulation, ENVI-met. A total of eight scenarios with UA of 0.3 and 0.7, UGC of 0%, 20% and 40% and UAR of 1.8 and 0.9, were simulated. Among these scenarios, the scenario simulated with low UA of 0.3, UGC of 20% and UAR of 1.8 has the greatest potential in improving urban microclimate. Comparing the scenarios with UAR of 1.8 and 0.9, it indicated that the scenario with large UAR is more effective than that with small UAR for UHI mitigation. Additionally, in the case of smaller UAR, diffusive highly reflective (HR) facade will not improve the UHI effect, whereas it might increase the UHI phenomenon in Osaka.

Keywords: UHI phenomenon; urban landscaping; urban albedo; urban aspect ratio; environmental simulation

1. Introduction

The urban heat island (UHI) effect is a well-documented climatic change phenomenon and is becoming very serious especially in the summer period due to the rapid increase of urban anthropogenic heat [1]. UHI intensity in hot climates may raise temperatures by 10 °C [2], resulting in increased discomfort and higher pollution levels, while it has a serious impact on the cooling energy consumption of buildings [3,4]. In order to mitigate the UHI effect, many studies have focused on defining the relationship between rising temperatures and different urban elements [5-7]. Santamouris et al. (2011) reviewed many articles relating to the UHI mitigation strategies, and showed that the mitigation strategies such as; highly reflective (HR) and emissive light colored materials, cool colored materials, phase change materials (PCMs) and dynamic cool materials used for building roofs or facades, increasing urban albedo (UA), green roofs (GR), etc. can significantly contribute to UHI mitigation and the improvement of urban environmental quality [8]. Also, other studies have focused on the micro-scale showing the influence of urban design on the climate [9,10]. Connors et al. (2013) showed that the intra-urban variations in temperatures are a significant feature rising from the UHI and largely result from urban elements such as urban structure (e.g. urban aspect ratio (UAR): height-to-width ratio (H/W)), urban green covering (UGC), UA, etc [11]. Doick and Hutchings (2013) showed
that vegetation has a key role to play in contributing to the overall temperature regulation of cities [12]. Informed selection and strategic placement of trees and green infrastructure can reduce the UHI and cool the air by between 2 °C and 8 °C, reducing heat-related streets and premature human deaths during high-temperature events.

Much research has shown that increasing the proportion of UGC or UA can decrease the urban temperatures, reduce energy consumption of buildings and improve outdoor thermal comfort. Among the strategies of mitigating UHI effect, HR coatings are being researched widely. Doulos et al. (2004) selected 93 pavement materials commonly used outdoors to increase the UA for UHI mitigation [13]. Bretz and Akbari (1997) applied HR coatings to residential buildings in California and Florida, contributing to cooling energy savings of 10%-70% [14]. Cozza et al. (2015) produced smart paints applied to building facades for UHI mitigation and energy conservation [15]. A total of five different black colorants produced in laboratory have been mixed with commercial paints and have been compared to the standard black colorant usually used for building paints. It showed that the surface temperature on the back of a painted support is lower as the total solar reflectance is higher, thus can be used for building energy conservation. Strategies of arranging UGC to mitigate UHI effect are also being studied by many researchers. Wang and Akbari (2016) analyzed the environmental effect of street tree planting patterns in a central area in Montreal using a simulation model [16]. It indicated that the correlation between tree cover and urban temperature is about 0.64 at summer mid-night. In the daytime, tree cover could reduce outdoor air temperature by 4 °C at the tree level of 20 m height and 2 °C at the tree level of 60 m height. Akbari (2002) demonstrated that urban shade trees could offer significant benefits in reducing building air-conditioning (AC) demand and improving urban air quality by reducing smog [17].

However, the implementation of these strategies above to mitigate UHI effect might worsen the phenomenon that it seeks to mitigate without considering regional resources and the local climate characteristics. In order to demonstrate the effect of UGC and UA on urban microclimate including outdoor air temperature ($T_a$) and mean radiant temperature ($T_{mr}$), this paper aims to analyze the environmental effect for a new residential area with 10,000 m$^2$ floor area located in Osaka, during one typical summer day (August 11, 2015), using an environmental simulation, ENVI-met. It will contribute to future UHI mitigation guideline development for urban planning in Osaka, Japan.

2. Methodology

2.1. Target region

The new residential area located in Osaka city (34.41°N; 135.3°E), Japan was selected to be simulated and analyzed for environmental effect in this study. As shown in Figure 1, the region is (X-axis) 100 m × (Y-axis) 100 m in area. A total of eight scenarios with different UA for building envelopes (rooftop and facade), different proportion of UGC and different UAR ($H/W$) were proposed, and detailed in Table 1. For eight scenarios, the area for buildings and roads is fixed, 25% of area for buildings and 15% of area for roads. The area for UGC is changed due to different proposed scenarios. Two types of UAR with 1.8 and 0.9 are simulated in this study.

2.2. Environmental simulation

In this study, the environmental simulation, ENVI-met, which is a 3D computer model that can analyze micro-scale thermal interactions within urban environments, was used to simulate the environmental conditions in the target region. The target region is simulated into a 3D geometry which includes buildings, vegetations, soils and receptors. One typical summer day (August 11, 2015) in Osaka was selected for simulation analysis. The start time of simulations is 07:00 in the morning and the end time is 07:00 of the next day with a total simulation time of 24 hours. The detailed initial input parameters of simulations are shown in Table 2, and the ENVI-met data flow is shown in Figure 2.
Figure 1. New residential area with 10,000 m² in Osaka City (I: UA for building envelopes (rooftop and facade): 0.3 or 0.7, UGC: 0%, UAR: 1.8; II: UA for building envelopes (rooftop and facade): 0.3 or 0.7, UGC: 20%, UAR: 1.8; III: UA for building envelopes (rooftop and facade): 0.3 or 0.7, UGC: 0%, UAR: 0.9; IV: UA for building envelopes (rooftop and facade): 0.3 or 0.7, UGC: 40%, UAR: 1.8).

Table 1. The new residential area with 10,000 m² floor area was simulated into eight scenarios.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>UA for building facade [-]</th>
<th>UA for rooftop [-]</th>
<th>Proportion of UGC [%]</th>
<th>UAR: H/W [-]</th>
<th>UA for pavement [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.3</td>
<td>0.3</td>
<td>0</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>0.3</td>
<td>0.3</td>
<td>20</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.7</td>
<td>0.7</td>
<td>0</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>0.7</td>
<td>0.7</td>
<td>20</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>0.3</td>
<td>0.3</td>
<td>40</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>0.7</td>
<td>0.7</td>
<td>40</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>0.3</td>
<td>0.3</td>
<td>0</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>0.7</td>
<td>0.7</td>
<td>0</td>
<td>0.9</td>
<td></td>
</tr>
</tbody>
</table>
Figure 2. Environmental simulation (ENVI-met) data flow. (http://www.envi-met.com/documents/onlinehelpv3/hs740.htm)

Table 2. Detailed initial input parameters for simulation analysis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start date and time (YYYY/MM/DD-HH:MM)</td>
<td>2015/08/11-07:00</td>
</tr>
<tr>
<td>End date and time (YYYY/MM/DD-HH:MM)</td>
<td>2015/08/12-07:00</td>
</tr>
<tr>
<td>Total simulation time (hr)</td>
<td>24</td>
</tr>
<tr>
<td>Output interval for receptors and buildings (min)</td>
<td>30</td>
</tr>
<tr>
<td>Wind speed measured in 10 m height (m/s)</td>
<td>3.0</td>
</tr>
<tr>
<td>Wind direction</td>
<td>Southwest</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>295.00 K (21.85 °C)</td>
</tr>
<tr>
<td>Building interior temperature (K)</td>
<td>299.15 K (26 °C)</td>
</tr>
<tr>
<td>Relative humidity in 2 m (%)</td>
<td>50</td>
</tr>
</tbody>
</table>

For the structure of the residential area in this simulation analysis, as shown in Table 1, asphalt material with a low-albedo of 0.15 is used as the pavement of the residential area for all the scenarios (scenario: A-H); the rooftop of buildings is covered with waterproof sheet and the building façade is covered with common ceramic tile both with low-albedo of 0.3 for four scenarios (A, B, E and G) and both with high-albedo of 0.7 for four scenarios (C, D, F and H). Two types of UAR with 1.8 and 0.9 and three types of common trees often used in Osaka are adopted in the simulation analysis. The characteristics (height and crown width) of trees are shown in Table 3.

Table 3. Height and crown width of trees in simulations with green covered scenarios.

<table>
<thead>
<tr>
<th>Tree types</th>
<th>Height (m)</th>
<th>Crown width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acer campestre</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>Privet</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Cypress</td>
<td>7</td>
<td>3</td>
</tr>
</tbody>
</table>

2.3. Receptors and sky view factors in simulated scenarios
A total of four measurement receptors are set in each proposed simulation (orange points described in Figure 1). The sky view factor (SVF) is the fraction of sky area when one looks up to the sky. An SVF of 1 is a completely open area, without any buildings or high objects obstructing the view, and an SVF of 0 is a completely closed indoor environment, thus the value of SVF usually varies from 0 to 1 for measurement receptors in the urban space [18]. The average SVF for each simulated scenario at human height level of 1.8 m is shown in Figure 3.

3. Results

3.1. Sky view factor (SVF)

Comparing the SVF of eight simulated scenarios, scenarios (G and H) are 0.42 with the highest SVF, followed by SVF of 0.28 for scenarios (A and C), SVF of 0.25 for scenarios (B and D), and the lowest SVF of 0.20 for scenarios (E and F). It showed that the larger the UGC and UAR, the smaller the SVF. Thus, it is considered that the SVF is strongly related to parameters of UGC and UAR.

3.2. Outdoor air temperature (Ta)

The change in outdoor air temperature (Ta) of 24 hours (2015/08/11 07:00-2015/08/12 07:00) at human height level of 1.8 m with 30 minutes interval output for eight simulated scenarios is shown in Figure 4. The maximum Ta (Ta_max), the minimum Ta (Ta_min) and the average Ta (Ta_avg) for the eight scenarios are shown in Table 4.
The analyzed results showed that:

- The $T_{a\text{-max}}$ during 24 hours occurs at 14:30 in the afternoon and the $T_{a\text{-min}}$ during 24 hours occurs at 06:00 in the morning for all the simulated scenarios.

- Comparing eight simulated scenarios, scenario B (UA: 0.3 + UGC: 20% + UAR: 1.8) has the lowest $T_{a\text{-max}}$ (37.06 °C), $T_{a\text{-min}}$ (15.83 °C) and $T_{a\text{-avg}}$ (26.35 °C). However, scenario H (UA: 0.7 + UGC: 0% + UAR: 0.9) has the highest $T_{a\text{-max}}$ (40.56 °C), $T_{a\text{-min}}$ (20.97 °C) and $T_{a\text{-avg}}$ (29.96 °C).

### 3.3. Mean radiant temperature ($T_{mrt}$)

Mean radiant temperature ($T_{mrt}$) shows the sum of all short-wave and long-wave radiation fluxes absorbed by human body. Thus, using $T_{mrt}$ is also important to evaluate the human thermal comfort. The change in mean radiant temperature ($T_{mrt}$) of 24 hours (2015/08/11 07:00-2015/08/12 07:00) at human height level of 1.8 m with 30 minutes interval output for eight simulated scenarios is shown in Figure 5. The maximum $T_{mrt}$ ($T_{mrt\text{-max}}$), the minimum $T_{mrt}$ ($T_{mrt\text{-min}}$) and the average $T_{mrt}$ ($T_{mrt\text{-avg}}$) for eight simulated scenarios are also shown in Table 4.

![Figure 4. Change in outdoor air temperature ($T_a$) of 24 hours from 2015/08/11 07:00 to 2015/08/12 07:00 with 30 minutes interval output at human height level of 1.8 m for eight simulated scenarios.](image)

**Table 4. The maximum $T_a$, minimum $T_a$ and average $T_a$ of 24 hours for eight simulated scenarios.**

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{a\text{-max}}$ (°C)</td>
<td>38.09</td>
<td>37.06</td>
<td>38.34</td>
<td>37.08</td>
<td>38.15</td>
<td>38.08</td>
<td>40.36</td>
<td>40.56</td>
</tr>
<tr>
<td>$T_{a\text{-min}}$ (°C)</td>
<td>20.74</td>
<td>15.83</td>
<td>20.78</td>
<td>16.90</td>
<td>19.55</td>
<td>20.49</td>
<td>20.93</td>
<td>20.97</td>
</tr>
<tr>
<td>$T_{a\text{-avg}}$ (°C)</td>
<td>28.45</td>
<td>26.35</td>
<td>26.87</td>
<td>26.80</td>
<td>28.37</td>
<td>28.73</td>
<td>29.78</td>
<td>29.96</td>
</tr>
<tr>
<td>$T_{mrt\text{-max}}$ (°C)</td>
<td>74.40</td>
<td>64.75</td>
<td>77.80</td>
<td>66.16</td>
<td>64.37</td>
<td>65.22</td>
<td>77.38</td>
<td>79.79</td>
</tr>
<tr>
<td>$T_{mrt\text{-min}}$ (°C)</td>
<td>15.02</td>
<td>10.29</td>
<td>15.39</td>
<td>11.44</td>
<td>13.83</td>
<td>14.84</td>
<td>15.13</td>
<td>15.48</td>
</tr>
<tr>
<td>$T_{mrt\text{-avg}}$ (°C)</td>
<td>37.85</td>
<td>32.57</td>
<td>39.65</td>
<td>33.82</td>
<td>31.40</td>
<td>32.37</td>
<td>40.88</td>
<td>42.28</td>
</tr>
</tbody>
</table>
The analyzed results showed that:

- The same as \( T_{\text{max}} \) and \( T_{\text{min}} \), \( T_{\text{mrt-max}} \) and \( T_{\text{mrt-min}} \) during 24 hours occurs at 14:30 in the afternoon and 06:00 in the morning respectively for all the simulated scenarios.

- Comparing eight simulated scenarios, scenario E (UA: 0.3 + UGC: 40% + UAR: 1.8) has the lowest \( T_{\text{mrt-max}} \) (64.37 °C) and \( T_{\text{mrt-avg}} \) (31.40 °C), scenario B (UA: 0.3 + UGC: 20% + UAR: 1.8) has the lowest \( T_{\text{mrt-min}} \) (10.29 °C). However, scenario H (UA: 0.7 + UGC: 0% + UAR: 0.9) has the highest \( T_{\text{mrt-max}} \) (79.79 °C), \( T_{\text{mrt-min}} \) (15.48 °C) and \( T_{\text{mrt-avg}} \) (42.28 °C).

### 3.4. Distributions of outdoor temperature (\( T_a \))

In order to better know the \( T_a \) distribution in the urban environment for eight simulated scenarios, images of \( T_a \) distribution in cross sections (X-Y and Y-Z) at 14:00 (August 11, 2015) for eight simulated scenarios are shown in Figure 6 and Figure 7, respectively.

The results showed that:

- **Figure 6** shows that the \( T_a \) of scenario B (UA: 0.3 + UGC: 20% + UAR: 1.8) and scenario D (UA: 0.7 + UGC: 20% + UAR: 1.8) is the lowest and that of scenario G (UA: 0.3 + UGC: 0% + UAR: 0.9) and scenario H (UA: 0.7 + UGC: 0% + UAR: 0.9) is the highest in the cross section (X-Y) at a human height level (1.8 m), compared to the other scenarios.

- **Figure 7** shows that building surface temperature for scenarios (C, D, F and H) with UA of 0.7 is higher than the other scenarios with UA of 0.3. The building surface temperature for scenario H is the highest.
Figure 6. Image of $T_a$ distribution at human height ($Z=1.8 \text{ m}$) in the cross section (X-Y) for eight simulated scenarios at 14:00, 2015/8/11.

Figure 7. Image of $T_s$ distribution at depth ($X=17 \text{ m}$) in the cross section (Y-Z) for eight simulated scenarios at 14:00, 2015/8/11.
Figure 8 shows the $T_\alpha$ distribution in the cross sections (X-Y) at human height level (1.8 m) for eight simulated scenarios at 14:00 (August 11, 2015). We can see that scenario A (UA: 0.3 + UGC: 0% + UAR: 1.8) and scenario C (UA: 0.7 + UGC: 0% + UAR: 1.8) have a similar distribution, scenario B (UA: 0.3 + UGC: 20% + UAR: 1.8) and scenario D (UA: 0.7 + UGC: 20% + UAR: 1.8) have a similar distribution, scenario E (UA: 0.3 + UGC: 40% + UAR: 1.8) and scenario F (UA: 0.7 + UGC: 40% + UAR: 1.8) have a similar distribution and scenario G (UA: 0.3 + UGC: 0% + UAR: 0.9) and scenario H (UA: 0.7 + UGC: 0% + UAR: 0.9) have a similar distribution.

4. Discussion

Comparing scenario A (UA: 0.3 + UGC: 0% + UAR: 1.8) to scenario C (UA: 0.7 + UGC: 0% + UAR: 1.8), the average $T_\alpha$ and $T_{net}$ for scenario A are respectively approximately 0.2 °C and 1.8 °C higher.
than these for scenario C. This indicates that high UA for building facades is not effective to mitigate UHI effect, whereas it might increase the UHI phenomenon. The reason is considered to be that the diffusive HR facade can reflect the incident sunlight into the open area if there are no obstacles [19]. However, for an urban environment, the thermal interaction between neighboring building facades has a significant impact on the urban microclimate due to the reflected sunlight from adjacent building façades. A study showed that an increase of 5 °C of $T_a$ in summer was recorded inside the buildings when high-albedo composed the building envelope in Las Vegas [20]. Thus, in the place of diffusive HR materials, retro-reflective (RR) materials, that can reflect the incident sunlight backwards to the source and reduce the UHI effect, are being researched as building façade materials by scholars globally [21,22].

Comparing scenario B (UA: 0.3 + UGC: 20% + UAR: 1.8) to scenario A (UA: 0.3 + UGC: 0% + UAR: 1.8), the $T_{a-avg}$ and $T_{mrt-avg}$ for scenario B are respectively approximately 2.1 °C and 5.3 °C lower than these for scenario A. Additionally, the $T_{a-avg}$ and $T_{mrt-avg}$ for scenario D (UA: 0.7 + UGC: 20% + UAR: 1.8) are respectively approximately 1.9 °C and 5.8 °C lower than these for scenario C (UA: 0.7 + UGC: 0% + UAR: 1.8). This indicates that the urban landscaping is more effective for UHI mitigation both decreasing $T_a$ and $T_{mrt}$ compared to strategies of using high UA for building facades.

Comparing scenario E (UA: 0.3 + UGC: 40% + UAR: 1.8) to scenario B (UA: 0.3 + UGC: 20% + UAR: 1.8), the $T_{a-avg}$ for scenario E is approximately 2.0 °C higher than that for scenario B, whereas the $T_{mrt-avg}$ for scenario E is approximately 1.2 °C lower than that for scenario B. Additionally, the $T_{a-avg}$ for scenario F (UA: 0.7 + UGC: 40% + UAR: 1.8) is approximately 1.9 °C higher than that for scenario D (UA: 0.7 + UGC: 20% + UAR: 1.8), whereas the $T_{mrt-avg}$ for scenario F is approximately 1.5 °C lower than that for scenario D. This indicates that increasing the proportion of UGC from 20% to 40% did not bring improvement in terms of decreasing $T_a$, whereas it could increase $T_{mrt}$. However, increasing the proportion of UGC can decrease the $T_{mrt}$. The reason is considered to be that too much UGC surrounding the urban area is likely to bring a negative effect on the ventilation of the city, trapping urban heat and leading to an increase of $T_a$.

A study on disaggregating and quantifying the influence of mutual shading and mutual reflection within a network of buildings revealed that the shading effect within inter-building effect (IBE) could reduce the energy consumption of buildings with a higher percentage of 28.4% in Miami, 10.5% in Washington, D.C. and 1.7% in Minneapolis during summer period [23]. Comparing scenario A (UA: 0.3 + UGC: 0% + UAR: 1.8) to scenario G (UA: 0.3 + UGC: 0% + UAR: 0.9), the $T_{a-avg}$ and $T_{mrt-avg}$ at human height level (1.8 m) for scenario A are respectively approximately 1.3 °C and 3.0 °C lower than these for scenario G. Additionally, the $T_{a-avg}$ and $T_{mrt-avg}$ at human height level (1.8 m) for scenario C (UA: 0.7 + UGC: 0% + UAR: 1.8) are respectively approximately 1.3 °C and 2.6 °C lower than these for scenario H (UA: 0.7 + UGC: 0% + UAR: 0.9). Thus, we can conclude that the large UAR of 1.8 is more effective than small UAR of 0.9 to mitigate the UHI effect for Osaka. The reason is considered to be that the shading effect within IBE in a high-rise high density urban environment plays a more significant role in terms of impact on building energy consumption and urban microclimate [23].

5. Conclusion and future work

In this study, the effect of UGC, UA and UAR on the UHI mitigation in terms of affecting $T_a$ and $T_{mrt}$ was analyzed using an environmental simulation in a new residential area of Osaka.

Increasing the proportion of UGC is more effective than strategies of increasing the UA for building facades in terms of mitigating UHI effect. However, too much UGC surrounding the city is likely to bring a negative effect on the ventilation of the city, trapping urban heat and leading to an increase of $T_a$, whereas increasing the proportion of UGC can decrease $T_{mrt}$. Therefore, it showed that increasing the proportion of UGC around the city to a relatively larger ratio will not be necessarily effective for improvement of urban environment.

Due to the effect of mutual reflection of diffusive HR envelopes within IBE in a high-rise high density urban environment, increasing the UA for building facades will not be effective to mitigate UHI effect, whereas it can increase the UHI phenomenon in Osaka. Thus, RR materials applied to building facades are being studied to replace the diffusive HR materials.
The scenario with large UAR is more effective than that with small UAR for UHI mitigation. It is considered to be that the effect of mutual shading within IBE in a high-rise high density urban environment plays an important role on saving energy consumption of buildings and improving urban microclimate.

For the future work, a new environmental simulation in which the RR envelope can be adopted should be developed to evaluate the effect of RR facades on UHI mitigation. Low-cost RR materials should be developed to replace the diffusive HR materials for application to building facades, together with urban landscaping to mitigate UHI effect. In addition, the maintenance of green planting should be carried out considering the maintenance cost in the future.

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Conflicts of Interest: The authors declare that there is no conflict of interests regarding the publication of this paper.

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