Study of a Simple Evaluation Method of Urban Heat Island Mitigation Technology using Upper-Air Data

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ABSTRACT

The upper-air data recorded at four towers located between Osaka city and eastern Osaka city indicate that the sensible heat flux released in the urban canopy layer causes the surface air temperature to rise. Methods based on the surface-boundary layer model were used for estimating the amount of sensible heat flux released and the coefficient of heat transfer from surface air to upper air by convection. The convection-heat transfer coefficient, changes in the air temperature with the release of sensible heat flux, and decrease in the air temperature due to the implementation of urban heat island mitigation strategies were estimated by using the observation data recorded at the four towers. The deviation in the convection-heat transfer coefficient of the surface-boundary layer model over a decade and across the four towers was almost negligible. The difference between the air temperatures in the daytime and nighttime changed by a factor of two or three with the change in the amount of sensible heat flux released.

Introduction

In Japan, the urban heat island (UHI) phenomenon (i.e., increased air temperature) that occurs in the urban area has been recognized as a serious problem. Various UHI mitigation strategies have been developed, and their effectiveness is determined by using them for various applications (e.g., cool roofs, green roofs, cool pavements, HVAC systems). Furthermore, the characteristics of each technology have been clear (AIJ 2007; Takebayashi and Moriyama 2007). However, an evaluation method for the effectiveness of these mitigation strategies has not been established; thus, there are only a few examples of the implementation of mitigation strategies for the UHI phenomenon. Therefore, it is necessary to develop an evaluation method for mitigation strategies so the residents and industries of Japan can make further technological advancements by implementing these strategies. In general, the evaluation of the effectiveness of UHI mitigation strategies is carried out by using meso- or small-scale numerical weather simulation models (Taha 1997). However, it is difficult to carry out numerical simulations for each strategy. The purpose of this study was to develop a simple evaluation method for the effectiveness of UHI mitigation strategies.

In the mesoscale weather simulation model, which is used for evaluating the effectiveness of UHI mitigation strategies, the lower layer of the one-dimensional surface-boundary layer model is coupled with the upper layer of the three-dimensional hydrodynamic turbulence model (University Corporation for Atmospheric Research; WRF Community). By estimating the heat budget of the ground surface, the amount of flux released into the atmosphere (e.g., momentum, heat, and moisture fluxes) is estimated. Recently, an urban-canopy model was incorporated in the surface-boundary layer model for precise estimation of the amount of flux (Masson 2000; Kusaka et al. 2001; Kondo et al. 2005).

The structure of the mesoscale weather-simulation model, which consists of the three-dimensional hydrodynamics model and the surface-boundary layer model, is shown in Figure 1. The surface-air temperature and wind velocity are calculated using the one-dimensional surface-boundary model; then, these results are set as the lower boundary condition of the three-dimensional hydrodynamics model. The amount of sensible heat flux released, which is estimated from the surface heat budget of the ground surface, is set as the lower boundary condition. Therefore, if we can obtain the upper-air data across the entire calculation domain, we can calculate the surface-air temperature and wind velocity by using only the one-dimensional surface-boundary layer model; then, these results are set as the lower boundary condition of the three-dimensional hydrodynamics model. The amount of sensible heat flux released, which is estimated from the surface heat budget of the ground surface, is set as the lower boundary condition. Therefore, if we can obtain the upper-air data across the entire calculation domain, we can calculate the surface-air temperature and wind velocity by using only the one-dimensional surface-boundary model, with precision similar to that of general mesoscale weather simulation models. This method is simple (i.e., it does not require three-dimensional calculations). In fact, it is difficult to acquire the upper-air data with a high-space resolution; in this study, we acquired the upper-air data at four observation points. However, these data were not compared with the mesoscale model (e.g., Weather
In this study, as shown in Figure 1, the upper-boundary condition of the surface-boundary layer model (i.e., the lower-boundary condition of the three-dimensional hydrodynamics model) was obtained directly. We installed observation instruments on four steel towers, with the cooperation of an electric power company and a phone company. The instruments were set from the west end to the east end of the Osaka plains. Observation data recorded by the instruments were used for calculating the upper-boundary condition of the surface-boundary layer model, and in particular, the change in the surface-air temperature and the change in the amount of sensible heat flux released were examined.

The relative location and distance of the four steel towers is shown in Figure 2, and images of the observation instruments are shown in Figure 3. The wind direction and velocity were recorded using a two-dimensional ultrasonic anemometer. The air temperature was measured using a thermistor-type thermometer. The observation height was determined to be located in the constant-flux layer. The observation period was 10 minutes. Nanko is a coastal area, Namba is an urban area, and Aramoto and Ishikiri are suburbs. Ishikiri is located at the foot of Mt. Ikoma. Each observation instrument was installed on the south side of the steel tower to reduce the effect of land and sea breezes, flowing in the east-west direction in the summer, on the tower. The observation instruments had photovoltaic panels, a battery, and a data storage device. The data were transmitted via wireless communication at the ground level. Furthermore, we used 10 years of data collected at the Osaka tower, which is located in Osaka city, to account for secular variations. It is located in an urban area, and its distance from the seashore is the same as that of Namba tower.

Outline of the Surface-Boundary Layer Model

The sensible heat flux in the one-dimensional surface-boundary layer model was defined as shown in (1).

\[ V = \alpha_c (\theta_0 - \theta_a) \]  

(1)

Here, \( V \) is the sensible heat flux (W/m²); \( \alpha_c \), convection-heat transfer coefficient (W/m²K); \( \theta_0 \), surface air potential temperature (K); and \( \theta_a \), upper air potential temperature (K).

The convection-heat transfer coefficient was expressed as shown in (2) on the basis of the Monin-Obukhov similarity theory.

\[ \alpha_c = \frac{C_p g \kappa u_*}{F_m F_h} \]  

(2)
where $C_p$ is the specific heat of air (=1.0 kJ/kg·K); $\gamma$, density of air (=1.2 kg/m³); $k$, von Karman constant (=0.35); and $u_a$, upper-wind velocity (m/s). $F_m$ and $F_h$ are integral values of the universal function (−). Businger’s experimental expressions were used for the universal function.

It is noted that this similarity theory can be used effectively for explaining the heat-transportation phenomenon in urban areas (Moriwaki and Kanda 2006). However, in the case of unstable weather conditions, the constant flux layer is not formed. Because similarity theory is generally used in mesoscale weather simulation models, and the main purpose of this study was to develop a simple evaluation method for the effectiveness of UHI mitigation strategies, we used this similarity theory even though it has certain limitations.

The parameters used in this model were the upper-wind velocity ($u_a$), roughness parameter ($z_0$), and difference in the upper- and surface-air potential temperatures ($\theta_u - \theta_s$). The upper-wind velocity and the upper- and surface-air potential temperatures were measured at the steel towers, and $z_0$ was assumed to be 1.5 m because Osaka city is almost urbanized. $\alpha_c$ was estimated using the aforementioned parameters. Some estimation methods for $z_0$ are recommended, for example, using geometric characteristics (e.g., building height and density) and turbulence statistics (e.g., friction speed), but in this study, it was assumed according to previous studies (Moriyama and Takebayashi 1999).

An outline of the surface-boundary layer model is shown in Figure 4. The sensible heat flux released from buildings and roads and the anthropogenic heat released from buildings and cars were discharged into the surface air, and the heat was transported to the upper air. When the amount of sensible heat flux and anthropogenic heat released was small, the change in the surface-air temperature was small. When the amount of heat flux transported to the upper air was large (i.e., when the heat did not remain in the surface air), the change in the surface-air temperature was again small.

![Figure 4. Surface-boundary layer model](image-url)
Convection-Heat Transfer Coefficient Estimated using Upper Observation Data

Change in Convection-Heat Transfer Coefficient Estimated using Observation Data Recorded at Osaka Tower

The convection-heat transfer coefficient was estimated using the wind velocity and upper-air potential temperature measured at the Osaka tower. The observation height was 120 m above ground level. The surface-air potential temperature was measured at the air-pollution monitoring station of Osaka city. The observation point was located approximately 2 m above the roof of the building, at the bottom of the Osaka tower. The estimation results are shown in Figure 4. All the data from July to September were used in the analysis in order to consider the average summer conditions. The observation point at which the surface-air potential temperature was measured was transferred in 1997 from the Tenma Junior High School to the Saihi Elementary School; however, both observation points are located close to the Osaka tower, and the observation results for air temperature showed almost the same tendency. As shown in Figure 5, the deviation in the convection-heat transfer coefficient over the decade was almost negligible.

Convection-Heat Transfer Coefficient, Estimated Using Observation Data Recorded at Four Towers

The convection-heat transfer coefficient was estimated using the wind velocity and upper-air potential temperature measured at the four towers and the surface-air potential temperature measured below the Osaka tower, as shown in Figure 6. The month of August was selected as the examination period because the rainy season continues until the end of July. Results were similar to the results for the observation data at Osaka tower. The difference between the upper- and surface-air potential temperatures was small at the Nanko tower; however, the convection-heat transfer coefficient was comparatively high. The reason for this is considered to be the high wind velocity in the coastal area.

The difference between the upper- and surface-air potential temperatures measured at the four towers was smaller than that between the potential temperatures measured at the Osaka tower. The reason for this is believed to be the difference in the ground-surface temperature recorded at these towers. The observation points, at which surface-air potential temperature was recorded, are located a small distance from the ground surface, below the four towers, but the distance of the observation point located below the Osaka tower is only 2 m from the top of the building roof. So, the observation instruments were installed close to the roofs of the buildings. Because the Namba tower is located in the downtown area, we set three instruments on telephone poles located in the urban area, and the average of the surface-air potential temperatures recorded by these three instruments was used as the surface-air potential temperature in Namba.

Examination of Changes in the Surface-Air Temperature with the Convection-Heat Transfer Coefficient

Examination of Observation Data Recorded at Osaka Tower

The hourly mean values and standard deviations in the convection-heat transfer coefficient from July 1 to September 30, which were estimated by the aforementioned method using the observation data recorded at the Osaka tower, are shown in Figures 7 and 8. The convection-heat transfer coefficient was approximately 100 W/m²K in the daytime and approximately 50 W/m²K in the nighttime. Thus, the standard deviation was large. The mean value was approximately 50 W/m²K in the nighttime.

Figure 5. Difference between upper- and surface-air potential temperatures (x-axis) and the convection-heat transfer coefficient (y-axis), estimated using observation data recorded at the Osaka tower.
and the standard deviation was approximately 30 W/m²K. Thus, the standard deviation depended greatly on the climatic conditions.

The change in the surface-air temperature $\Delta \theta$ (K), when an additional amount of sensible heat flux $\Delta V$ (W/m²) was released into the surface air, was estimated. In this case, the sensible heat flux transported from the surface air to the upper air was expressed as shown in (3). Upper-air temperature $\theta_a$ also changed as a result of the changing sensible heat flux; however, its quantity was considerably smaller in comparison with $\Delta \theta$ because the upper-air exists in the constant flux layer.

$$V + \Delta V = \alpha' \left( (\theta_a + \Delta \theta) - \theta_s \right)$$  \hspace{1cm} (3)

where $\Delta \theta$ causes $\alpha$ to change to $\alpha'$. Thus, it was necessary to recalculate $\alpha'$ by convergence calculation. However, if $\Delta V < V$, $\alpha' = \alpha$. Then, (4) can be derived from (1) and (3).

$$\Delta \theta = \Delta V / \alpha_c$$  \hspace{1cm} (4)

In this study, evaluation of the effectiveness of UHI mitigation strategies was carried out by assuming that $\Delta V$ takes a negative value and $\alpha' < \alpha$. Therefore, (4) gives an underestimate of $\Delta \theta$ implying that the evaluation was incorrect. However, (4) was adopted in this study because it simplifies calculations.

The change in the surface-air temperature, estimated from (4) using the convection-heat transfer coefficient shown in Figure 7, when additional sensible heat flux of 10 W/m² was released into the surface air, is shown in Figure 9. When the convection-heat transfer coefficient was small, the change in the surface-air temperature was large. For the same amount of additional sensible heat flux released, the difference between the surface-air temperature in the daytime and nighttime changed by a factor of two or three. However, because the standard deviation in the convection-heat transfer coefficient was large in the nighttime (i.e., the average convection-heat transfer...
coefficient of 50 W/m$^2$K changed to 20 W/m$^2$K) $\Delta \theta$ increased from 0.2° C/10 W/m$^2$ to 0.5° C/10 W/m$^2$. In the nighttime, it may be said that the surface-air temperature increased greatly, with a small change in the additional sensible heat flux released because the atmosphere was unstable.

**Examination of Observation Data Recorded at Four Towers**

The hourly mean values and standard deviations in the convection-heat transfer coefficient, which were estimated by the aforementioned method using the observation data recorded at the four towers, are shown in Figures 10 and 11. A comparison of the hourly mean values recorded at the Osaka tower over the decade showed that the change in the surface-air temperature in Namba was small in the morning. The reason for this was considered to be the small difference between the upper- and surface-air potential temperatures recorded at this observation point than that between the temperatures recorded at the other observation points. In the daytime, sea breezes blow into the urban area, which makes the climatic conditions unstable, and therefore a constant flux layer may not be formed. It is believed that heat is transported due to relatively large-scale turbulence in the sea breeze under this condition. The standard deviation in the convection-heat transfer coefficient over the decade was almost equal to that estimated using the observation data recorded at the Osaka tower, but its value was large because the number of sampled data was small.

The change in the surface-air temperature with the convection-heat transfer coefficient is shown in Figure 12a. It was assumed that the lowest value of the convection-heat transfer coefficient was 1 W/m$^2$K. The tendency for the coefficient to be small in the daytime and large in the nighttime was clear, but the deviation was large. To avoid bad weather conditions from affecting the calculations, a fine weather day (i.e., a day with incident solar radiation of 12 MJ/m$^2$ and no precipitation) was selected. The calculation result in the case of the fine weather day is shown in Figure 12b. The deviation was still large. The standard deviation in the convection-heat transfer rate coefficient is thought to be because the release of a certain amount of additional sensible heat flux was almost zero. The lowest value of the convection-heat transfer coefficient was assumed to be 10 W/m$^2$K, as shown in Figure 12c. In the case of stable climatic conditions, calculating the changes in the surface-air temperature with the convection-heat transfer coefficient was difficult.

The surface-air temperature increased by approximately 0.1° C in the daytime and approximately 0.2° to 0.3° C in the nighttime, with the release of additional sensible heat flux of 10 W/m$^2$. This result was similar to that observed in the case of the
data recorded at the Osaka tower. The temperature recorded at the four steel towers rarely changed; however, that recorded at the Namba tower changed greatly in the morning on the fine weather day. The change in the hourly mean values of the upper- and surface-air potential temperatures from August 1 to 31, 2006, is shown in Figure 12. The difference between the upper- and surface-air potential temperatures recorded at the Nanko tower and that recorded at the other observation points was approximately 2°C in the daytime. However, this difference was small in the nighttime. The change in both the upper- and surface-air potential temperatures was regulated by the sea breezes blowing into Nanko, which is a coastal area. As a result, the difference in the upper- and surface-air potential temperatures in the coastal area was almost equal to that in the potential temperatures in the inland area. Thus, the convection-heat transfer coefficients estimated at all the observation points were almost equal. Therefore, this model did not account for the advection, but it appeared to have some influence.

Evaluation of Effectiveness of UHI Mitigation Strategies in Decreasing Surface Air Temperature

UHI mitigation strategies were implemented and their effectiveness was evaluated by estimating the decrease in the surface-air temperature by the aforementioned method. UHI mitigation strategies implemented on buildings and road surface coatings were selected. Parameters were set according to previous studies, as shown in Table 1 (Takebayashi and Moriyama 2007). The sensible heat flux released from the surfaces, where UHI mitigation strategies were implemented, was calculated by using the surface-heat budget model. The model consisted of a surface-heat budget equation and a one-dimensional unsteady conduction equation (Takebayashi and Moriyama 2007). The changes in the surface-air temperature and amount of sensible heat flux released are shown in Figure 12. The base condition was assumed to consist of a concrete surface (60%) and asphalt surface (40%).

The decrease in the amount of sensible heat flux released was calculated by assuming that the UHI mitigation strategy was implemented on all types of concrete surfaces (i.e., green roofs, white cool roofs, gray cool roofs) or all types of asphalt surfaces (i.e., water-keeping asphalt, water-keeping concrete, water-keeping block). But the relationship between each building and their mutual radiation exchange was not considered here.

The sensible heat flux released from each of the aforementioned surfaces in the day- and nighttime was estimated, and the results are shown in Table 2. The decrease in the surface-air temperature was calculated by estimating the
decrease in the sensible heat flux released from each surface and changes in the surface-air temperature with the release of additional sensible heat flux. The reduced surface-air temperatures recorded at the Nanko (coastal) and Namba (urban) towers are shown in Tables 3 and 4. Because the effect of the mitigation strategies in reducing the amount of sensible heat flux released was small in the nighttime, the decrease in the surface-air temperature was small, too. If 10 W/m² of anthropogenic heat was reduced uniformly in the nighttime, the surface air temperature was reduced by 0.21° C in Nanko and by 0.19° C in Namba.

Figure 12. Change in surface-air temperature with release of additional sensible heat flux of 10 W/m²
(a) Data collected on all days (b) Data collected on fine weather day (c) Data collected with the lower limit of the convection-heat transfer coefficient set at 10 W/m²K

Figure 13. Hourly mean values of observation results recorded at four towers from August 1 to 31
(a) Upper-air potential temperature (b) Surface-air potential temperature (c) Difference between upper- and surface-air potential temperatures

Table 1. Parameters of the surface-heat budget model

<table>
<thead>
<tr>
<th>Material</th>
<th>Asphalt</th>
<th>Concrete</th>
<th>Green roof</th>
<th>White cool roof</th>
<th>Gray cool roof</th>
<th>Water keeping asphalt</th>
<th>Water keeping concrete</th>
<th>Water keeping block</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albedo (-)</td>
<td>0.044</td>
<td>0.357</td>
<td>0.15</td>
<td>0.74</td>
<td>0.36</td>
<td>0.37</td>
<td>0.153</td>
<td>0.233</td>
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<tr>
<td>Evaporative efficiency (-)</td>
<td>0</td>
<td>0</td>
<td>0.14</td>
<td>0</td>
<td>0.084</td>
<td>0.029</td>
<td>0.035</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity (W/mK)</td>
<td>0.84</td>
<td>1.59</td>
<td>0.60</td>
<td>1.59</td>
<td>1.59</td>
<td>0.87</td>
<td>0.99</td>
<td>0.65</td>
</tr>
<tr>
<td>Thermal capacity (J/m³K)</td>
<td>700000</td>
<td>100000</td>
<td>290000</td>
<td>100000</td>
<td>100000</td>
<td>150000</td>
<td>500000</td>
<td>300000</td>
</tr>
</tbody>
</table>

Table 2. Estimation results of sensible heat flux released in night- and daytime

<table>
<thead>
<tr>
<th>W/m²</th>
<th>Green roof</th>
<th>White cool roof</th>
<th>Gray cool roof</th>
<th>Water keeping asphalt</th>
<th>Water keeping concrete</th>
<th>Water keeping block</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daytime</td>
<td>34.5</td>
<td>92.6</td>
<td>0.73</td>
<td>30.1</td>
<td>11.2</td>
<td>11.0</td>
</tr>
<tr>
<td>Nighttime</td>
<td>4.21</td>
<td>0.58</td>
<td>0.00</td>
<td>2.57</td>
<td>1.02</td>
<td>1.10</td>
</tr>
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</table>

Table 3. Reduced surface-air temperature recorded at Namba tower (coastal)

<table>
<thead>
<tr>
<th>°C</th>
<th>Green roof</th>
<th>White cool roof</th>
<th>Gray cool roof</th>
<th>Water keeping asphalt</th>
<th>Water keeping concrete</th>
<th>Water keeping block</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daytime</td>
<td>0.42</td>
<td>1.19</td>
<td>0.01</td>
<td>0.38</td>
<td>0.14</td>
<td>0.13</td>
</tr>
<tr>
<td>Nighttime</td>
<td>0.08</td>
<td>0.01</td>
<td>0.00</td>
<td>0.05</td>
<td>0.02</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 4. Reduced surface-air temperature recorded at Namba tower (urban)

<table>
<thead>
<tr>
<th>°C</th>
<th>Green roof</th>
<th>White cool roof</th>
<th>Gray cool roof</th>
<th>Water keeping asphalt</th>
<th>Water keeping concrete</th>
<th>Water keeping block</th>
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<tbody>
<tr>
<td>Daytime</td>
<td>0.48</td>
<td>1.37</td>
<td>0.01</td>
<td>0.43</td>
<td>0.16</td>
<td>0.15</td>
</tr>
<tr>
<td>Nighttime</td>
<td>0.07</td>
<td>0.01</td>
<td>0.00</td>
<td>0.04</td>
<td>0.02</td>
<td>0.02</td>
</tr>
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</table>
**Conclusion**

The upper-air data recorded at four towers located between Osaka city and eastern Osaka city indicated that the sensible heat flux released into the urban canopy layer caused the surface air temperature to rise. Methods based on the surface-boundary layer model were used for estimating the amount of sensible heat flux released and the coefficient of heat transfer from surface air to upper air by convection.

The convection-heat transfer coefficient estimated at the Osaka and the four towers showed that the standard deviation in the coefficient over a decade and across the four towers was almost negligible.

Even if the difference in the upper- and surface-air potential temperatures was small, the convection-heat transfer coefficient estimated at the Nanko tower (coastal) was confirmed to be large because of the high wind velocity associated with sea breezes. The convection-heat transfer coefficient estimated at the Namba tower (urban) was less than that estimated at the other observation points in the morning because sea breezes blow inland during this time and climatic conditions become unstable.

The change in the surface-air temperature with the release of additional sensible heat flux into the surface air was estimated using the convection-heat transfer coefficient. The difference between daytime and nighttime air temperature changed by a factor of two or three when the amount of additional sensible heat flux released was the same. Because the atmosphere is stable in the nighttime, the surface-air temperature changed greatly with the release of additional sensible heat flux.

UHI mitigation strategies have been implemented, and their effectiveness has been evaluated by estimating the decrease in surface-air temperature from day to night. The aforementioned method can be used to evaluate the effectiveness of UHI mitigation strategies, not only by estimating the amount of sensible heat flux released from buildings and pavement-surface coating systems, but also by estimating the decrease in the amount of anthropogenic heat released.

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