Study on Influence of the Change of Land Cover Ratio on Urban Thermal Environment – No.1 Analysis by Mean of the Meso-scale Numerical Simulation Model

Hideki Shibaike¹, Kazuya Itemadani² and Hideki Takebayashi³

Abstract

Summer effects as well as winter influences of architectural counter measures for summer urban climate mitigation are numerically evaluated by using the meso-scale CFD model. In order to confirm the solution accuracy of the model, sensitivities of numerical results to the discretizations of time and space are examined. Then, numerical simulations are carried out for which each of the counter measures among high reflectivity land cover, exterior thermal insulation, reduction of anthropogenic heat release and rooftop green is considered for the area of Kyoto and Osaka City. In summer results, counter measures show obvious effects of temperature reduction, however the dominant period and magnitude is different from each other. High reflectivity land cover and rooftop green show significant temperature decrease in daytime, on the other hand, exterior thermal insulation shows it in nighttime.

1. Introduction

In the previous papers, we analyzed the regional climate in Kinki district by numerical prediction tool based on Mellor-Yamada model under typical summer conditions (Ooka 1997 and Takebayashi 2002), in which urbanized area of Kobe and Osaka were the target regions. Besides, we mainly focused on how to tailor boundary and initial conditions in order to reproduce the current situation in these regions.

The purpose of this investigation is to evaluate the summer effects of architectural counter measures, as well as to estimate winter influences of them in order to mitigate summer urban climate in Kyoto and Osaka area by using the meso-scale CFD model. This model is based on the modified Colorado State Meso-scale Model (CSU-MM) (Pielke 1974, Ulrickson/Mass 1990 and Kessler/Douglas 1992) with modified input values for several surface boundary conditions (Ichinose 1997).

2. Outline of the adopted meso-scale model

The model takes into account hydrostatic equilibrium and the Boussinesq approximation. The governing equations are momentums, conservation of thermodynamic energy, conservation of moisture and continuity etc, within a three-dimensional terrain-following coordinate system. A diagnostic equation for pressure and surface heat budget is included. The lateral boundary conditions are assumed zero-gradient. The soil to a depth of 0.5 m is also divided into 11 layers of varying thickness. The constant temperature at a depth of 0.5 m is prescribed.

¹ Department of Architecture and Design, Faculty of Engineering and Design, Kyoto Institute of Technology, Mtsugasaki, Sakyo, Kyoto 606-8585, Japan, MailTo:Hideki.Shibaike@dad.kit.ac.jp, Http://shibaike.dad.kit.ac.jp/
² Construction Division, Asanuma Corporation, 12-6 Higashikohzu-cho, Tennohji, Osaka 543-8688
³ Department of Architecture and Civil Engineering, Faculty of Engineering, Kobe University, Rokkodai, Nada, Kobe 657-8501, Japan, MailTo:thideki@kobe-u.ac.jp, Http://www.arch.kobe-u.ac.jp/~ta1/
The energy balance on the interface between soil and atmosphere is given in equation (1), which directly reflects the counter measure for the summer urban climate mitigation.

\[
Q_{\text{surf}} = SR_{\text{surf}} + IR_{\text{surf}} + \rho c \mu \theta_s + \rho L v \theta_q - \varepsilon \sigma T_{\text{surf}}^4 - \rho c k \frac{\partial T}{\partial z} + A_c (1)
\]

Here, the left hand side of equation (1) means heat energy to drive soil surface temperature. Terms on the right hand side show solar radiation, long wave radiation from atmosphere, sensible heat transfer, latent heat transfer, long wave radiation from soil in which the value of emissivity assumes to 0.98, conduction heat flux into soil and anthropogenic heat release from left to right respectively.

3. Sensitivity analyses and accuracy on the current situation

In order to evaluate numerical accuracy on reproducing the current situation of the whole area of the Kinki district including Kyoto and Osaka, numerical investigations by the meso-scale model are performed. Sensitivities of numerical results against time intervals and spatial discretizations are analyzed on the current situation.

Tab. 1: Initial and boundary conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Season</th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start time of calculated period</td>
<td>1995.7.10 6:00 AM</td>
<td>1997.1.16 6:00 AM</td>
<td></td>
</tr>
<tr>
<td>Topographic relief</td>
<td>Digital national land information of Japan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial air pressure</td>
<td>1010 hPa</td>
<td>1010 hPa</td>
<td></td>
</tr>
<tr>
<td>Bottom surface temperature of the ground</td>
<td>26.5 K</td>
<td>6.0 K</td>
<td></td>
</tr>
<tr>
<td>Sea surface temperature</td>
<td>25.0 K</td>
<td>14.0 K</td>
<td></td>
</tr>
<tr>
<td>Top surface temperature of the ground</td>
<td>30.5 K</td>
<td>4.0 K</td>
<td></td>
</tr>
<tr>
<td>Gradient of potential temperature</td>
<td>4.2 K/km</td>
<td>4.0 K/km</td>
<td></td>
</tr>
<tr>
<td>Wind velocity and direction at the ceiling boundary</td>
<td>1.5 m/s and SSW</td>
<td>1.5 m/s and NNE</td>
<td></td>
</tr>
</tbody>
</table>

Tab. 2: Parameters on the ground surfaces

<table>
<thead>
<tr>
<th>Surface Type</th>
<th>Diff. on air temperature</th>
<th>Diff. on ground surface temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>0.18 (0.20)</td>
<td>0.56 (0.05)</td>
</tr>
<tr>
<td>Meadow</td>
<td>0.14 (0.18)</td>
<td>0.38 (0.05)</td>
</tr>
<tr>
<td>Building site</td>
<td>0.18</td>
<td>0.5</td>
</tr>
<tr>
<td>1722.094</td>
<td>5.3 x 10^-7</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1: The calculation geometry with the grading lattice

Fig. 2: Temperature differences between results of the uniform and grading lattices
The handling geometry is shown in Figure 1 with the grading lattice. The boundary and the initial conditions are shown in Table 1. Parameter values for the heat budget equation on the ground surface are shown in Table 2. Here, the zone including Kyoto and Osaka in Figure 1 with equally spaced lattice is evaluated as the investigation area with three series of numerical condition changes. The temporal variations on temperature and relative humidity of Kyoto shown in the following parts are the calculated values in the mesh including Kyoto local meteorological observatory.

First, the calculated result on spatial discretizations of the grading lattice is compared with that of uniform lattice with 2 km interval. The adopted time step is 5 seconds for both of them. The two kinds of differences on ground level temperature profiles in Kyoto do not show remarkable variations and amplitudes. However the temperature profiles of the grading lattice decrease slightly from those of the uniform one in daytime, and the tendency is reversed in nighttime (Figure 2).

Next, influences of the spatial interval for uniform lattices are numerically evaluated. Four kinds of uniform lattices with the interval of 2, 4, 8 or 16 km are examined, where the adopted time step is five seconds. Judging from the relation of the root mean square difference from the finest results (2 km) of the ground level air temperature versus the interval of the spatial lattice, the RMS difference increases with the interval of the spatial lattice. Although there is little fluctuation of RMS differences in 4 km interval, the fluctuation of every 3 hours differences increases remarkably when the interval of the spatial lattice becomes larger.

Then, influences of the time step on grading lattices are numerically evaluated. Seven cases of calculations are executed on the grading lattice of Figure 1 of which the adopted time step is changed to 1, 2.5, 5, 7.5, 10, 15 or 20 seconds. Judging from the correlation between the calculated values on the time step of 5 or 20 seconds and the observed values of ground level air temperature in the investigated area, the result on the time step of 20 seconds looks scarce correlation. The correlation coefficient on the results of the time step of 5 seconds or less to the observed values does not show the enormous discrepancy.

Finally, the calculated results in summer and winter are compared with the observed data of Kyoto City. The observed data of air temperature and relative humidity at Kyoto district meteorological observatory are averaged to the temporal profiles in the representative day, since the purpose of this investigation is not the forecasting to reproduce the situation on a specific day but the estimation of the climatic standard situation for the period. In order to avoid complex operation for averaging wind velocity and wind direction, the observed values on 31 July 1995 and 17 January 1997 are used directly for summer and winter respectively. The calculated values correspond well to those of observed temperature in summer and winter respectively. For relative humidity, the difference is rather little in daytime, but large in nighttime. Although the hygroscopic influence of vegetations and ground covers seems to cause these differences, quantitative analyses should be left as the future problem (Figures 3 and 4). However there exists a little difference in wind velocity, it roughly agrees with the observed value (Figure 5).

4. **Summer effects and winter influences of urban climate mitigation strategies**

In order to mitigate summer urban climate, several cool down technologies for extremely elevated surface temperature in daytime by the modification of the surface coatings for roads and buildings are selected. The summer effects and winter influences are examined on the typical sunny days of summer and winter in the area of Kyoto and Osaka. The following five kinds of modification scenarios are assumed. And those results are compared with the current reproduction case (Base) described in Section 3.

- **Case1**: High reflectivity of roads and buildings (Original albedo of 0.18 is increased to 0.40 or 0.60 for roads or building sites respectively).
- **Case2**: Exterior thermal insulation of building sites (The original values for thermal conductivity and thermal diffusivity of 1.52 and 7.20×10⁻² are changed to 3.72*10⁻² (W/mK) and 1.06×10⁻⁶ (m²/s) in ground layers of 0.05 m depth on building sites respectively).
Case 3: Green cover for building rooftops (The original value 0.0 of evaporation efficiency on building sites is increased to 0.30 for summer or 0.05 for winter respectively).

Case 4: Reduction of anthropogenic heat release (The original value of 30 is decreased to 15 (W/ m²) on roads and building sites).

Case 5: High reflectivity and Exterior thermal insulation (The combination of Case 1 and Case 2).

Exceptionally, Case 4 is only calculated for the summer condition.

For all cases, summer differences of the ground level air temperature in Kyoto are evaluated against the current situation (Base) and are shown in Figure 6. Case 1 or Case 3 has an effect to decrease daytime air temperature in summer. Case 2 has a predominant effect to decrease nighttime air temperature according to the reduction of ground surface temperature, however it increases daytime air temperature of about 0.5 K. Case 5 has an effect to decrease air temperature through a day. Comparing with the other cases, Case 4 has a weaker effect to decrease nighttime air temperature. The temperature difference is about 0.5 K at 21:00.

Case 1, Case 2, and Case 5 show similar temporal variations in summer and winter. On the other hand, Case 3 has only a summer effect and almost no winter difference. Figure 7 shows the spatial distribution of temperature difference between Case 3 and Base at 15:00. It also describes the above mentioned tendency of Case 3. The summer effect brought by green on rooftops depends on the fact that evapotranspiration accelerates latent heat transfer, and decreases the ground surface temperature then inhibits sensible heat transfer. The winter difference is eliminated by the fact that the smaller evaporation efficiency and the colder air temperature decrease evapotranspiration in vegetation. Humidity ratio increases as time elapses from the sunrise to sunset in summer. This profile describes evaporation cooling of green on rooftops well.

5. Conclusion

The meso-scale CFD simulations have been carried out for scenarios, in which counter measures among high reflectivity land cover, exterior thermal insulation, reduction of anthropogenic heat release and rooftop green were exclusively considered to the area of Kyoto and Osaka City. Summer effects in Kyoto city on the reduction of air temperature have been estimated as follows. The maximum and the average values are 1.03 K and 0.58 K for high reflectivity land cover, 1.24 K and 0.63 K for rooftop green, and 1.29 K and 0.31 K for exterior thermal insulation respectively. Former two show predominant effect in daytime while the last one shows it in nighttime. Furthermore, the combination of high reflectivity land cover and exterior thermal insulation have been confirmed to be effective through a day as 1.26 K as the maximum at nighttime and 0.83 K as the average. Rooftop green is the counter measure that slightly influences the air temperature reduction in winter. However the others affect negatively.

![Fig. 3: Comparison of calculated and observed results for summer in Kyoto](image1)

![Fig. 4: Comparison of calculated and observed results for winter in Kyoto](image2)
Fig. 5: Comparison of calculated and observed wind fields for summer (15:00)

Fig. 6: Summer Temperature differences for counter measures in Kyoto

Fig. 7: Differences between Case3 and Base at 15:00 (Left: Summer, Right: Winter)

Bibliography


