NUMERICAL PREDICTION OF HEAT ISLAND MITIGATION EFFECT ON DECREASE IN AIR TEMPERATURE IN TOKYO


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1. INTRODUCTION

The intensity of urban heat island is known to be stronger as city size (for example population of city) (Oke, 1973). In Tokyo 23 wards (hereinafter referred to as “Tokyo”) with more than eight million people, urban heat island phenomenon is actualized and feared as a factor of increase in heatstroke patients and raising cooling energy consumption in summer. Therefore, Tokyo Metropolitan Government promotes some heat island mitigation measures concerning with urban greening, reducing anthropogenic heat, and so on.

In introducing heat island mitigation measures, it is important to grasp these faculties in advance. A three dimensional numerical simulation is thought to be one of the most effective tools for this purpose. In previous studies, three-dimensional numerical simulations have been performed in order to predict the contribution of some influential factors like land coverage or anthropogenic heat to urban heat island (Kimura and Takahashi, 1991). By using a three-dimensional numerical simulation with the horizontal distribution of surface coverage and anthropogenic heat, the effect of mitigation measures on decrease air temperature can be evaluated with their various spatial arrangement patterns in urban area. On the other hand, it is required to pay attention to the adequacy of numerical model by comparing its results with field observation data.

In this study, firstly, a three-dimensional numerical simulation model is compared with field observation data, and secondly, the model is applied to Tokyo in order to estimate the effect of heat island mitigation measures concerning with urban greening, water retentive pavement, high light-reflective paint, and reducing anthropogenic heat on decrease in air temperature. Here, the amount of these mitigation measures with their spatial distribution is determined as these expected values in 2030.

2. NUMERICAL MODEL

A three-dimensional numerical simulation model used in this study is developed by authors. The basic equations are in Table-1, and the schematic image of the model is shown in Figure-1, respectively. The model is composed of two parts. The one is the ‘atmospheric model’ and the other is the ‘surface model’.

In the atmospheric model, atmospheric temperature, specific humidity, and three-dimensional wind velocities are calculated unsteadily by finite-difference-methods with the hydrostatic and Boussinesq approximation. The horizontal resolution of the model is one or a few kilometers. The basic equations are the equation (1)-(6) in Table-1.

In the surface model, the heat transfer to atmosphere is calculated under the influence of solar radiation, atmospheric radiation, and anthropogenic heat. Surface temperature is calculated from heat balance equation shown in the equation (7). The effect of heat storage into surface materials is considered with heat conductive equation in the equation (8). In this surface model, it is possible to calculate the heat...
Table 1 Basic equations of numerical model

Equations in atmosphere
\[
\begin{align*}
\frac{\partial u}{\partial t} + \frac{\partial (mu)}{\partial x} + \frac{\partial (nu)}{\partial y} + \frac{\partial (nv)}{\partial z} &= fh - h\theta + \frac{g\beta}{\theta - \Theta} \frac{\partial \theta}{\partial z} + \frac{\partial}{\partial x}\left(hK_{nu} \frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(hK_{nu} \frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial z}\left(hK_{nu} \frac{\partial u}{\partial z}\right) + \frac{z^2}{\rho} \frac{\partial}{\partial z}\left(K_{nu} \frac{\partial u}{\partial z}\right) \quad (1) \\
\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} + \frac{\partial (wh)}{\partial z} &= -fh - h\theta + \frac{g\beta}{\theta - \Theta} \frac{\partial \theta}{\partial z} + \frac{\partial}{\partial x}\left(hK_{vh} \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(hK_{vh} \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(hK_{vh} \frac{\partial h}{\partial z}\right) + \frac{z^2}{\rho} \frac{\partial}{\partial z}\left(K_{vh} \frac{\partial h}{\partial z}\right) \quad (2)
\end{align*}
\]

\[
\frac{\partial \pi}{\partial t} = \frac{h}{\theta} \frac{\partial \theta}{\partial t} \quad (3)
\]

\[
\frac{\partial \theta}{\partial t} + \frac{\partial h \theta u}{\partial x} + \frac{\partial h \theta v}{\partial y} = \frac{\partial}{\partial x}\left(hK_{\theta u} \frac{\partial \theta}{\partial x}\right) + \frac{\partial}{\partial y}\left(hK_{\theta v} \frac{\partial \theta}{\partial y}\right) + \frac{z^2}{\rho} \frac{\partial}{\partial z}\left(K_{\theta \theta} \frac{\partial \theta}{\partial z}\right) + \frac{Q}{\rho c_p} \quad (4)
\]

\[
\frac{\partial q}{\partial t} + \frac{\partial h \theta q u}{\partial x} + \frac{\partial h \theta q v}{\partial y} = \frac{\partial}{\partial x}\left(hK_{\theta q u} \frac{\partial q}{\partial x}\right) + \frac{\partial}{\partial y}\left(hK_{\theta q v} \frac{\partial q}{\partial y}\right) + \frac{z^2}{\rho} \frac{\partial}{\partial z}\left(K_{\theta \theta} \frac{\partial q}{\partial z}\right) + \frac{M}{\rho} \quad (6)
\]

Equations at and into surface
\[
\left(1 - \alpha \right) \tau \left(S_x + (L_x - L_y)\right) = H - IE - S \quad (7)
\]
\[
\frac{\partial T_x}{\partial t} = \frac{k_x}{\rho c_p} \frac{\partial^2 T_x}{\partial y^2} \quad (8)
\]

Equations for urban canopy
\[
V_{(i)} = \frac{\Psi_{(i)}}{k} \left(\theta_{(i)} - \bar{\theta}\right) \quad (9)
\]
\[
V_{(i)} = V_{(i)} \frac{\exp(0.5c_c) - \exp(-0.5c_c)}{\exp(c_c) - \exp(-c_c)} \quad (10)
\]
\[
H_{(i)} = \rho_c c_p \frac{\kappa^2 V_{(i)}}{g_{(i)}} \left(T_{(i)} - \bar{\theta}\right) + Q_{(i)} \quad (11)
\]
\[
H_{(i)} = \rho_c c_p \left(0.01 \sqrt{W_i} \right) \left(T_{(i)} - \bar{\theta}\right) + Q_{(i)} \quad (12)
\]
\[
H_{(i)} = \rho_c c_p \frac{\kappa^2 V_{(i)}}{g_{(i)}} \left(T_{(i)} - \bar{\theta}\right) + Q_{(i)} \quad (13)
\]
\[
\left(W_{(i)}^2 + 2W_{(i)} \right) H_{(i)} = \left(W_{(i)}^2 + 2W_{(i)} \right) H_{(i)} + 4W_{(i)} H_{(i)} \quad (14)
\]
\[
H_{(i)} = C_{(i)} \rho_c c_p \left(\frac{V_{(i)} + V_{(i)}^2}{2} \right) \left(\theta_{(i)} - \bar{\theta}\right) \quad (15)
\]
budget by finer horizontal resolution than the atmospheric model by bundling up the heat budgets belong to same atmospheric grid.

Furthermore, a simplified urban canopy model is adopted for urban surface modeling in order to consider the effect of buildings on radiation and wind velocity. The principal equations of the urban canopy model are the equation (9)-(12). In this urban canopy model, the surface temperatures of roof, wall, and road are predicted, respectively. Furthermore, the air temperature in a ravine of buildings (hereinafter referred to as “surface air temperature”) can be predicted. The needed numerical parameters for geometric pattern of buildings are height, width, and interval of buildings averaged in each horizontal numerical grid. In non-urban area, on the other hand, land surface is regarded as a plane and a roughness model is applied.

3. COMPARISON OF NUMERICAL RESULTS WITH FIELD DATA

3.1 Field data

In order to evaluate the numerical model, we use the field observation data with METROS (Metropolitan Environmental Temperature and Rainfall Observation System) set up by Tokyo Metropolitan Research Institute for Environmental Protection and Tokyo Metropolitan University (Mikami et al., 2003). The distribution of observation points is shown in Figure-2. METROS20 is a system to observe air temperature, relative humidity, wind velocity, wind direction, air pressure, and rainfall at 20 points of the top of buildings in Tokyo. METROS100 is to observe air temperature and relative humidity at 100 points of 1.5m height of ground level in Tokyo.

The effectiveness of METROS is to have high-density continuous observation points. Especially for air temperature and relative humidity just above ground level, METROS has 100 observation points over Tokyo (61500 ha). The METROS data with such high resolution can grasp the horizontal distribution of temperature over Tokyo in detail.

3.2 Numerical condition

In this study, a numerical simulation of the model is carried out on a typical summer day of August 29, 2002. The meteorological conditions of solar radiation and the vertical profile of air temperature and humidity are needed for simulation. Here, these data are obtained from the observation data by Japan Meteorological Agency.

The horizontal domain of simulation is 388 km from
west to east and 348 km from south to north, respectively (see in Figure-3). A variable mesh is used in the horizontal area. In the area of 35km×35km includes Tokyo (shown in Figure-2), horizontal grid size is 1km in atmosphere and 0.5km at surface. In the fringe of horizontal domain, the grid size becomes broader from 1km to 4km with distance from Tokyo.

In each surface grid, it is needed to set parameters to characterize surface properties. Here, altitude and surface coverage (occupancy ratio of sea, forest, grass, urban, and so on) are set up from GIS data by Geographical Survey Institute of Japan. In addition, geometry of buildings for the urban canopy model and anthropogenic heat are estimated similarly with GIS data by Tokyo Metropolis and Road Traffic Census data by Ministry of Land Infrastructure and Transport. As for anthropogenic heat data, they are set up as time-varying values in two forms, namely, sensible heat and latent heat.

### 3.3 Results

Numerical simulation of the model is compared with METROS data in a typical summer day of August 29, 2002. The distribution of horizontal wind velocity at three symbolic points of time is shown in Figure-4 for numerical simulation and field data by METROS20. In numerical results, wind velocity is small at 06:00; sea breeze toward NNW-ward can be seen at 14:00; and wind direction changes into NNE-ward at 20:00. The same features can be seen in field data.

For temperature, on the other hand, Figure-5 is distribution of surface air temperature for numerical simulation and field data by METRO100. In numerical results, the highest temperature reveals in center of Tokyo at 06:00, NW-ward of center of Tokyo at 14:00, and northward of center of Tokyo at 20:00. These results concern wind direction (see Figure-4), that is, the leeward of center of Tokyo becomes hotter. The same features can be seen in field data.

From the comparison mentioned above, we confirmed that the numerical results are in good agreement with the observation of horizontal distribution of air temperature, wind velocity, and wind direction near the surface.

### 4. ESTIMATION OF EVAPORATION EFFICIENCY FOR MITIGATION MEASURES

In order to estimate the effect of heat island mitigation measures by numerical simulation, it is needed to determine the surface physical parameters for roof greening and water retentive pavement. The evaporation efficiency, which is one of the important surface parameters, is estimated from the surface heat budget field data of roof greening and water retentive pavement observed by Tokyo Metropolitan Research Institute for Environmental Protection (Yokoyama et al., 2004) and Institute of Civil Engineering of Tokyo Metropolitan Government (Minegishi et al., 2002), respectively. For this estimation, the urban canopy model is picked out from the three-dimensional model and used as a vertical column model in order to evaluate surface heat balance. Meteorological conditions of wind velocity, air temperature and air humidity just upon urban canopy layer is set up from the field-measured data. The parameter values of the evaporation efficiency for
Figure-4 The simulated wind velocity at 45m height (upper three figures) and the wind velocity measured by METRS20 converted into 45m height by an exponential function (lower three figures) at 6:00, 14:00, and 20:00.

Figure-5 The simulated surface air temperature (upper three figures) and the air temperature measured at 1.5m height by METROS100 (lower three figures) at 6:00, 14:00, and 20:00.
roof greening and water retentive pavement are estimated by trial and error comparing with the model and the above observation heat budgets. As the example of estimation for roof greening, surface heat balance is shown in Figure-6 for a field measurement and four numerical cases with different value of the evaporation efficiency. In this case, the evaporation efficiency of roof greening is presumed about 0.2. Similarly, the evaporation efficiency of water retentive pavement is presumed about 0.05.

5. NUMERICAL PREDICTION OF MITIGATION EFFECTS

5.1 Mitigation

Finally, the effect of heat island mitigation measures on decreasing in temperature is estimated by the three-dimensional numerical simulation. Here, a mitigation scenario is supposed by introducing five kinds of mitigation measures mentioned below, simultaneously.

1) Introducing roof greening into 45.0% of roof area of buildings with over 1000 square meters of a building site and greening into 4.4% of urban ground surface in Tokyo
2) Introducing water retentive pavement into 29% of road in central area of Tokyo (see Figure-3)
3) Introducing high light-reflective paint into 20% of building roofs in Tokyo
4) Decrease in 41.5% of anthropogenic heat from automobiles in Tokyo by improvement of fuel cost and increase in travel speed of cars
5) Decrease in 21.5% of anthropogenic heat of houses and 26.5% of buildings for business use in Tokyo by improvement of thermal insulation efficiency of buildings and improvement of system for energy conservation

The numerical values for these mitigation measures are set up as expected values for Tokyo in 2030. The distribution of each measure is shown in Figure-7.

5.2 Results

Another numerical simulation in a typical summer day condition (August 29, 2002) is carried out, but with the future condition after mitigation measures in 2030. The difference between two numerical results with and without the five measures mentioned above reveals the effect of these measures. The surface air temperatures of two cases without and with mitigations are shown in Figure-8 with the temperature difference between these two cases. Decrease in the area-averaged temperature over Tokyo (61500ha) is predicted to be about 0.5K in daytime, and 0.2K in nighttime, respectively. In
central area of Tokyo (1600ha), on the other hand, temperature decrease is predicted to be about 0.8K in daytime.

Horizontal distribution of change in surface air temperature at 6:00, 14:00, and 20:00 is shown in Figure-9. It is clear that the decrease in temperature is large in central area of Tokyo. In addition, temperature decrease is noticeable in the leeward of central area of Tokyo (see Figure-4). This is thought to be a phenomenon caused by decreasing the heat advection from central area of Tokyo.

Furthermore, numerical cases for introducing each mitigation measure mentioned above are carried out. The difference between two numerical results with and without each measure at 14:00 is shown in Table-2. In the scenario of this study, urban greening shows the largest value in decrease in surface air temperature. In central area of Tokyo, the effect of measures related to decreasing anthropogenic heat are seems to be large.

6. CONCLUSIONS

The three-dimensional numerical simulation is carried out in order to estimate the effect of heat island mitigation measures on decrease in air temperature in Tokyo. Here, mitigation measures are assumed concerning with urban greening, water retentive pavement, high light-reflective paint, and reducing anthropogenic heat. The amount of these measures is assumed as expected values for Tokyo in 2030. In daytime, decrease in area-averaged air temperature is predicted about 0.5K over Tokyo and 0.8K over central area of Tokyo. Furthermore, it is found that the remarkable decrease in temperature reveals on the leeward of central Tokyo.

In this study, the simulation is carried out under a very calm meteorological condition. The evaluation of measures under various wind condition is remained as future work.

REFERENCES

Kimura, F. and Takahashi, S., 199: The Effects of
Table-2 The effect of each mitigation measure on decrease in surface air temperature

<table>
<thead>
<tr>
<th>mitigation</th>
<th>Area averaged value in Tokyo</th>
<th>Area averaged value in central area of Tokyo</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>introduction ratio *</td>
<td>difference in temperature</td>
</tr>
<tr>
<td>(1) Urban greening</td>
<td>6.5 %</td>
<td>-0.20 K</td>
</tr>
<tr>
<td>(2) Water retentive pavement</td>
<td>0.2 %</td>
<td>-0.01 K</td>
</tr>
<tr>
<td>(3) High light-reflective paint</td>
<td>5.1 %</td>
<td>-0.09 K</td>
</tr>
<tr>
<td>(4) Decrease in anthropogenic heat from automobile</td>
<td>41.5 %</td>
<td>-0.08 K</td>
</tr>
<tr>
<td>(5) Decrease in anthropogenic heat from buildings</td>
<td>20.4 %</td>
<td>-0.06 K</td>
</tr>
</tbody>
</table>

* Here, the 'introduction ratio' means the ratio of introduced area to all objective area for (1), (2), and (3), and the ratio of decrease in anthropogenic heat to total anthropogenic heat for (4) and (5).
