NOTES AND CORRESPONDENCE

Thermal and Geometric Controls on the Rate of Surface Air Temperature Changes in a Medium-Sized, Midlatitude City

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ABSTRACT

Gradual cooling in the evening forms a wintertime nocturnal urban heat island. This work, with a mesoscale model involving urban canopy physics, is an examination of how four thermal and geometric controls—anthropogenic heat \(Q_F\), heat capacity \(C\), thermal conductivity \(k\), and sky-view factor \(\phi_s\)—modify the rate of surface air temperature changes \(\Delta T/\Delta t\). In particular, the time dependence is diagnosed through numerical experiments. The controls \(Q_F\) and \(k\) are major agents in the evening, when \(Q_F\) changes the evening \(\Delta T/\Delta t\) linearly and \(k\) is logarithmic. The effects of \(C\) and \(\phi_s\) are large in the morning and in the afternoon with those of \(k\). The impact of \(Q_F\) is, however, substantial only in the evening. Because the time dependence of \(C\) and \(k\) is different, the thermal inertia used as a parameter in the urban climate studies should be divided into two parameters: \(C\) and \(k\). To improve the thermal environment in urban areas, the modification of \(Q_F\) and \(k\) could be effective.

1. Introduction

One aspect of the urban climate known as a heat island has become a problem in some cities with global warming. As an example, there is some anxiety that infectious diseases, through mosquitoes that survived warmer winters, would expand into subtropical or extratropical cities.

Kumamoto is a typical medium-sized, midlatitude city that is located in southwestern Japan (32.81°N, 130.71°E, 38 m; Fig. 1). The population is about 660 000, making it the third largest, administratively, in the Kyushu district. In February, the mean minimum temperature on calm, fine winter days increased from 1.8°C in the 1960s to 0.7°C in the 1990s (\(0.08°C\) yr\(^{-1}\)), and the inhabitants have become worried about the increase of Japanese encephalitis, an infectious disease. It is, therefore, important to evaluate the increase of the wintertime minimum temperature in detail.

On calm, fine winter days, the minimum temperature in Kumamoto is 0.8°C higher than that in Kosa (Fig. 2, dotted lines), which is a small village 21 km to the southeast (32.65°N, 130.81°E, 35 m; Fig. 1) with a population of 12 000. As shown in Fig. 2, the difference in the minimum temperature at 0600 Japan standard time (JST) is caused by differences in the rate of tempera-
ture changes $\Delta T/\Delta t$ for 4 h from 1530 to 1930 JST (Fig. 2, solid lines). The cooling rate in Kosa changes to be smaller at around 1930 JST while that in Kumamoto is still large, resulting in the alternation of $|\Delta T/\Delta t|$ at this time (Fig. 2, solid lines). Thus, the gradual cooling from 1530 to 1930 JST in Kumamoto forms a warmer condition before sunrise, that is, a nocturnal urban heat island, although Kosa may be somewhat under the influence of Kumamoto (cf. Lowry 1977). The nocturnal urban heat island seems to be developed from the late afternoon to the evening and to persist until the following morning, with weakening in Kumamoto. Figure 8.14 of Oke (1987), which is a schematic figure, also exhibits similar tendencies in temperature variations. Figure 2 of this work provides observational support for Oke’s figure.

Many studies have examined which control is major for the change of $\Delta T/\Delta t$ in the evening that contributes to form the wintertime nocturnal urban heat island (cf. Oke 1982). For instance, using a simple energy balance...
model developed by Johnson et al. (1991), Oke et al. (1991) pointed out that the sky-view factor \( \psi_s \) and thermal inertia \( \mu \) were equally important for the formation of an urban heat island. In addition, Kimura and Takahashi (1991) and Ichinose et al. (1999) identified how anthropogenic heat \( Q_F \) was essential for the evening \( \Delta T/\Delta t \) in the Tokyo metropolitan area. Furthermore, Atwater (1972) and Oke et al. (1991) pointed out that pollutants were less important for the formation of an urban heat island.

Some researchers recently reevaluated the effects of any controls using mesoscale models involving urban canopy physics (e.g., Martilli et al. 2002; Atkinson 2003; Kusaka and Kimura 2004a). The use of such a mesoscale model may allow more rigorous confirmation for the effects on \( \Delta T/\Delta t \) of thermal and geometric controls with local atmospheric circulation. This work, with the mesoscale model developed by Kusaka and Kimura (2004a,b), is an examination of the time dependence on \( \Delta T/\Delta t \) of thermal and geometric controls. Because Kusaka and Kimura (2004a) have diagnosed the geometric controls of the urban canopy in detail, emphasis in this work is placed on the thermal controls. Taking advantage of numerical experiments, the thermal inertia \( \mu \), which has been treated as a thermal control, has been divided into two components, the heat capacity \( C \) and the thermal conductivity \( k \), based on the definition \( \mu = (Ck)^{1/2} \). The impacts of \( C \) and \( k \) on \( \Delta T/\Delta t \) were then diagnosed separately. Tables 2.1 and 7.4 in Oke (1987) may be referenced for the concrete values of some materials.

The realistic time variation of \( Q_F \) in Kumamoto is used in this work to examine the effects on \( \Delta T/\Delta t \) in the evening. Because there are few studies discussing the time dependence on \( \Delta T/\Delta t \) of these controls in detail, this work identifies it for the thermal controls \( Q_F, C \), and \( k \) and for the geometric control \( \psi_s \) through idealized numerical experiments. Such sensitivity experiments are still needed, because an urban climate is highly complex and is dependent on many factors. The accumulation of results allows quantitative evaluation of the controls on urban climate and contributes to future city planning in the real world. It is noteworthy that no attempt is made in this work to reproduce observations (Fig. 2), because a two-dimensional model, which is coarser than the real 3D world, is used for the numerical experiments, and the parameter sets are somewhat arbitrary.

In the remainder of this paper, section 2 contains an outline of the mesoscale model and numerical experiments conducted for this work. Section 3 contains the time dependence on \( \Delta T/\Delta t \) of four controls—\( Q_F, C, k, \) and \( \psi_s \). Section 4 is a summary with some discussion.

### 2. Outline of the mesoscale model and numerical experiments

The local circulation model (LCM), into which Kusaka and Kimura (2004a) embedded urban canopy physics (Kusaka et al. 2001), is employed in this work. Because the performance of LCM has been thoroughly examined by Kusaka and Kimura (2004a,b), the details are omitted to avoid lengthiness. Following the method in Kusaka and Kimura (2004b), the two-dimensional version of zonal and vertical directions (hereinafter referred to as the LCM2D-C) was used in this work to exclude the complexity that may appear because of the local circulation. The physical processes in LCM2D-C are outlined in Table 1.

In the model, the grid interval is set to be 2 km and the number of grids is 100, resulting in a domain of about 200 km in the zonal direction. In the vertical direction, the layer thickness increases exponentially from 30 m at the surface to 250 m for the highest layer. The lowest layer corresponds to the lower part of the surface layer, and the mean temperature represents the surface air temperature uniformly reflecting heat fluxes from diverse urban surfaces. The meaning of this temperature is different from that measured at 1.5-m height in observatories.

In the model domain, the surface is covered by grassland and an artificial town with a width of 8 km is put in the center. The numerical experiments are then conducted by modifying the properties of the central area. The values of the fundamental parameters in the artificial and natural (grassland) surfaces are listed in

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### Table 1. Outline of the physical processes in LCM2D-C.

<table>
<thead>
<tr>
<th>Physics</th>
<th>Assumption and scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic equations</td>
<td>Hydrostatic, anelastic model; terrain-following height coordinate; no Coriolis force</td>
</tr>
<tr>
<td>Radiation</td>
<td>Time-dependent solar scheme for shortwave (Kusaka et al. 2000); empirical form for longwave (Kondo 1994)</td>
</tr>
<tr>
<td>Turbulence</td>
<td>Mellor–Yamada level-2 model (Mellor and Yamada 1974)</td>
</tr>
<tr>
<td>Land surface</td>
<td>Slab grass model and single-layer urban canopy model (Kusaka and Kimura 2004a,b)</td>
</tr>
<tr>
<td>Lateral boundary</td>
<td>Periodic condition</td>
</tr>
<tr>
<td>Top boundary</td>
<td>Wave radiation condition (Klep and Durran 1983)</td>
</tr>
</tbody>
</table>
Table 2. Fundamental parameters of artificial and natural surfaces in LCM2D-C. The natural surface is represented by grassland.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Artificial surface</th>
<th>Natural surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albedo</td>
<td>0.15</td>
<td>0.2</td>
</tr>
<tr>
<td>Moisture availability</td>
<td>0.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Roughness length (m)</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Zero displacement height (m)</td>
<td>2.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Anthropogenic heat (W m⁻²)</td>
<td>13.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Heat capacity (×10⁶ J m⁻³ K⁻¹)</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Thermal conductivity (W m⁻¹ K⁻¹)</td>
<td>0.8</td>
<td>0.4</td>
</tr>
<tr>
<td>Sky-view factor</td>
<td>0.45</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 2. To increase the reality of the parameters, we referred to the values observed in earlier studies (Kusaka et al. 2000; Sugawara 2001; Sugawara et al. 2001; Kusaka and Kimura 2004b) and those listed in textbooks (Oke 1987; Kondo 1994).

In Table 2, \( Q_e \) was estimated from the published data for gas and electricity in Kumamoto and for the downtown traffic density. Hourly data had been recorded for electricity and traffic density, whereas the data for gas were the total consumption over the winter months—that is, December, January, and February. Therefore, we assumed that the time variation of gas consumption was similar to that of electricity, referring to earlier studies (Kimura and Takahashi 1991; Ichinose et al. 1999). Because the traffic density was measured at the widest and most crowded downtown boulevard, which has six lanes, we reduced the value by one-third to represent the usual streets in Kumamoto. Summing up these three sources of heat, we estimated an hourly mean of 13.0 W m⁻² and the time variation shown in Fig. 3.

The time variation of \( Q_e \) (Fig. 3) seems to reflect the human activity in a typical medium-sized city in Japan—that is, the rapid increase from 0600 to 0800 JST corresponds to the beginning of morning activity. The value reaches a maximum at around 0900 JST and gradually decreases until 1300 JST. After noon, the emissions again increase slowly, reaching a second maximum at around 1900 JST, which is concurrent with the evening rush hour. The value then decreases until 0500 JST the next morning. Note that the time variations of electricity and traffic density are similar to the pattern shown in Fig. 3, suggesting that the time lag by the insulation of buildings is not large in Kumamoto. The pattern is also similar to that drawn in Ichinose et al. (1999, their Fig. 6), which was estimated from data collected in Tokyo, although their hourly mean is much larger than 13.0 W m⁻².

Table 3 lists the parameter sets for numerical experiments. In the list, case 1 represents the control run for an idealized city, most of which is covered by an artificial surface (80%; Table 2). Based on the parameters in case 1, sensitivity experiments (cases 2–5) were designed to isolate the effects of \( Q_e \) (case 2), \( C \) (case 3), \( k \) (case 4), and \( \psi_0 \) (case 5), where each parameter is replaced by one-half of (cases 2–4) or 2 times (case 5) that in case 1 (Table 3; boldfaced numbers). Because it is impossible to add the effects of each parameter to flat fields (no urban canopy) in LCM2D-C, the above designs were contrived following the method in Atkinson (2003). Further experiments, which were based on a finer change of parameters, were also performed for specific verification.

The LCM2D-C was run for 36 h for a numerical experiment, beginning at 0300 local solar time (LST) 1 January. The initial conditions were then set based on the data in Kumamoto and the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis (Kalnay et al. 1996), in which the lapse rate of the potential temperature was 0.005 K km⁻¹, the relative humidity was 50%, and westerly winds were set at 2.0 m s⁻¹. These values were assigned equally to all of the vertical model layers.

3. Impacts of four controls on the rate of surface air temperature changes

Figure 4 exhibits the variations of surface air temperature in the central part of a model domain (dotted) and the \( \Delta T/\Delta t \) (solid) in case 1 (thick lines). The counterparts, which were set to be flat grassland without urban canopy [referred to as the flat-field (FF) run], are also added to demonstrate the performance of LCM2D-C (thin lines). The LCM2D-C displays good
performance despite having two dimensions. For instance, the cooling rate in case 1 is gradual in the evening, and the rate becomes larger than that in the FF run after 2000 LST; as a result, the temperature difference decreases until sunrise. In addition, the warming rate in the morning is larger in the FF run than in case 1 (see also Fig. 2; solid lines). Because of the use of the two-dimensional LCM2D-C, which has no forcing from another dimension, we no longer compare the outputs to the observations (Fig. 2).

Instead, comparisons were performed between the outputs of case 1 and those of cases 2–5 (Fig. 5). The impacts of $C$ (triangle), $k$ (square), and $\psi_\theta$ (cross) are equally and synchronously large from 1300 to 1700 and from 0600 to 1100 LST, when the negative (positive) values in the afternoon (morning) accelerate cooling (warming) during that time. The values in $C$, $k$, and $\psi_\theta$ are also negative during the night, indicating that these controls make the nocturnal cooling large; in particular, the values in $C$ are negatively large (triangle).

In the evening, at around 1830 LST, the impacts of $Q_F$ (filled circle) and $k$ (square) are specifically large, which indicates that the cooling rate becomes large in the evening, if the parameters are replaced by one-half of their values. It is interesting that only two controls predominantly modify the $\Delta T/\Delta t$ in the evening. The impact of $C$ (triangle) is near zero and that of $\psi_\theta$ (cross) is less than one-third of the values in $Q_F$ and $k$ at around that time.

The effects of $Q_F$ on $\Delta T/\Delta t$ are mostly small except in the evening. However, the positives in $Q_F$ at night yield a tendency opposite to that with the negatives in $C$, $k$, and $\psi_\theta$. The alternation of signs in $Q_F$ from negative to positive at around 2000 LST enhances the change of the slope in the temperature variation at around this time (see also Fig. 2; thin dotted line). In the morning, the impacts of $Q_F$ are smaller than those of the other three controls but exhibit a complicated feature—that is, the values are negative from 0600 to 0900 LST but are positive after 0900 LST (Fig. 5). The change of polarities could be attributed to the time variability of $Q_F$ in the morning: an increase from 0600 to 0600 JST and a decrease from 0900 to 1300 JST (Fig. 3). Halving $Q_F$ suppresses the morning temperature rise until 0900 JST and strengthens it from 0900 to 1300 JST relatively. If there were no time variation in $Q_F$, the control would have no effect on the time variability in temperature.

To examine the sensitivity of $Q_F$ and $k$ in the evening in more detail, additional numerical experiments were

**Table 3.** Parameter sets for numerical experiments. The parameters are for the central part of the model domain, where the ratio of grassland is 20%, whereas the outside is set to be 100% grassland. Case 1 is the control run of an idealized urban area. Cases 2–5 are designed for sensitivity experiments based on halving or doubling of each parameter in case 1. Boldfaced figures are the changed parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anthropogenic heat (W m$^{-2}$)</td>
<td>13.0</td>
<td>6.5</td>
<td>13.0</td>
<td>13.0</td>
<td>13.0</td>
</tr>
<tr>
<td>Heat capacity ($\times 10^6$ J m$^{-3}$ K$^{-1}$)</td>
<td>2.0</td>
<td>2.0</td>
<td>1.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Thermal conductivity (W m$^{-1}$ K$^{-1}$)</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.4</td>
<td>0.8</td>
</tr>
<tr>
<td>Sky-view factor</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
<td>0.9</td>
</tr>
</tbody>
</table>

**Fig. 4.** Time variations of the surface air temperature (dotted line) and the rate of change (solid line) for case 1 (thick lines) and for the counterparts of a flat grassland field (thin lines). The hours of sunset and sunrise on 1 January are set to be 1751 and 0610 LST in the model.

**Fig. 5.** Effects on $\Delta T/\Delta t$ (°C h$^{-1}$) of $Q_F$ (case 2 – case 1: closed circles), $C$ (case 3 – case 1: triangles), $k$ (case 4 – case 1: squares), and $\psi_\theta$ (case 5 – case 1: times signs).
The numerical experiments revealed that $Q_F$ and $k$ effectively modify the $\Delta T/\Delta t$ in the evening at around 1830 LST, whereas the effects of $C$ and $\psi_i$ are small at around that time. Here the response of $\Delta T/\Delta t$ to the change of $Q_F$ is linear, whereas that of $k$ is logarithmic in the evening. Although some earlier studies have noted the importance of $Q_F$ for the formation of an urban heat island (e.g., Kimura and Takahashi 1991; Ichinose et al. 1999), this work identified that the effects of $Q_F$ on $\Delta T/\Delta t$ were restrictive in the evening. The controls $C$ and $k$, which are factors of a complex control called thermal inertia, apparently indicate different time dependence on $\Delta T/\Delta t$. Therefore, these controls should be distinguished in the study of an urban heat island. On the one hand, there are differences in $C$ and $k$ in the evening; these are equally effective in the late afternoon and in the morning with the effects of $\psi_i$. During the night, the responses of $\Delta T/\Delta t$ to $Q_F$ and $C$ are relatively large but have opposite polarities.

The four controls—$Q_F$, $C$, $k$, and $\psi_i$—have different time dependences on $\Delta T/\Delta t$. To improve the thermal environment in urban areas, these controls should all be sufficiently modified. In particular, it would be effective to decrease $Q_F$ in the evening and make $k$ smaller by changing the materials of the urban fabric. However, further study is needed for a quantitative elucidation of the impact of each control. In particular, the evaluation of $Q_F$ seems to be weak because of the difficulty of the estimation. With regard to the quantitative evaluation of the control of an urban heat island, city planning should be performed in the future.

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