Moderation of Summertime Heat Island Phenomena via Modification of the Urban Form in the Tokyo Metropolitan Area

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ABSTRACT

This study investigated the moderation of the urban heat island via changes in the urban form in the Tokyo metropolitan area (TMA). Two urban scenarios with the same population as that of the current urban form were used for sensitivity experiments: the dispersed-city and compact-city scenarios. Numerical experiments using the two urban scenarios as well as an experiment using the current urban form were conducted using a regional climate model coupled with a single-layer urban canopy model. The averaged nighttime surface air temperature in TMA increased by $0.34 \pm 0.8$ C in the dispersed-city scenario and decreased by $0.18 \pm 0.8$ C in the compact-city scenario. Therefore, the compact-city scenario had significant potential for moderating the mean areal heat-island effect in the entire TMA. Alternatively, in the central part of the TMA, these two urban-form scenarios produced opposite effects on the surface air temperature; that is, severe thermal conditions worsened further in the compact-city scenario because of the denser population. This result suggests that the compact-city form is not always appropriate for moderation of the urban-heat-island effect. This scenario would need to combine with other mitigation strategies, such as the additional greening of urban areas, especially in the central area. This study suggests that it is important to design a plan to adapt to higher urban temperatures, which are likely to ensue from future global warming and the urban heat island, from several perspectives; that is, designs should take into account not only climatological aspects but also impacts on urban inhabitants.

1. Introduction

Most regions of Japan experienced record heat levels in the summer of 2010. In August of 2010 the Tokyo meteorological station observed the highest monthly-mean surface air temperature (29.6°C) on record (between 1876 and 2012). In the Tokyo metropolitan area (TMA), 16,477 people were hospitalized for heat stroke between July and September of 2010 (Fire and Disaster Management Agency 2010), and 621 people died of heat stroke over the full year (Ministry of Health Labor and Welfare 2011). Heat stroke tends to develop frequently in the daytime when high temperatures are experienced. In the summer of 2010, however, about one-half of the people who died of heat stroke in Tokyo died during the night, and many were single elderly people (Tokyo Metropolitan Government Bureau of Social Welfare and Public Health 2010). Heat-related health issues during the night, including heat stroke and sleep disruption, in addition to those during the day, are becoming a significant social issue in the TMA, especially in the central area, where high nighttime temperatures can be experienced.

The summertime climate in the TMA is characterized by conditions of high temperature and humidity that
lead to discomfort for the inhabitants. The climate in this region is significantly affected by two stationary high pressure systems: the Bonin high and the Okhotsk high. The appearance in Japan of an active Bonin high, which is a subtropical anticyclone located in the south of the country, blocks typhoons and prevents disturbances from passing through Japan, which brings fine weather in the TMA (Ueda et al. 1995; Yasunaka and Hanawa 2006). Conversely, an intensified Okhotsk high over the Okhotsk Sea generates a cold northeasterly wind in the northern part of Japan and causes cold summer weather with cloudy conditions (Yasunaka and Hanawa 2006). The hot summer of 2010 was reported to be caused by the following conditions, typical of a hot summer: 1) midtropical-spheric warming, which seemed to be affected by the end of El Niño and the beginning of La Niña; 2) intensification of the Bonin high; and 3) weakening of the Okhotsk high (Japan Meteorological Agency 2011). Note also that the long-term warming trend has also been implicated in the hot summers experienced in recent years, including the summer of 2010. The surface air temperature in August in Tokyo increased by about 1.4°C during the 80 years from 1931 to 2010 (Japan Meteorological Agency 2011), which is associated with local urbanization and global warming due to the increased emission of anthropogenic greenhouse gases (e.g., Fujibe 2009). The frequency of hot summers, such as that of 2010, is projected to increase in Japan in the future because of global climate change (Solomon et al. 2007; Japan Meteorological Agency 2005; Kusaka et al. 2012). Thus, countermeasures against hot humid summer conditions in the TMA are required.

Moderation of the urban heat island is a potential method to improve uncomfortable summer conditions in urban areas. Moreover, such moderation is expected to become part of an adaptation strategy for global climate change because urban-heat-island mitigation should be mostly implemented by local governments (Coutts et al. 2008; Adachi et al. 2012). Many methods have been proposed to mitigate urban-heat-island effects, such as changes in the urban form (Oke 1984; Scherer et al. 1999), greening of parking lots and building walls (Onishi et al. 2010; Takebayashi and Moriyama 2009), increasing roof albedo (e.g., Takebayashi and Moriyama 2007; Krayenhoff and Voogt 2010; Oleson et al. 2010), and changes in pavement materials (Takebayashi and Moriyama 2012). Of these possible measures, this study focused on changes in the urban form.

Many previous studies have reported the effects of land-use changes on urban heat islands in relation to the expansion and reduction of the urban area in several urban cities, including the TMA (e.g., Kimura and Takahashi 1991; Kusaka et al. 2000; Van Weverberg et al. 2008; Miao et al. 2009; Aoyagi et al. 2012). Adachi et al. (2012) estimated the urban-heat-island intensity (UHII) in the TMA by replacing urban areas with grassland in a numerical model. The sensitivity experiment indicated that the average UHII in August in the TMA was approximately 1°C in the 1990s. Papangelis et al. (2012) conducted numerical experiments and estimated the cooling effect of replacing the industrial/commercial area with a large green park in Athens, Greece. They indicated that the introduction of a large urban park had a cooling effect of more than 5°C at nighttime when compared with the original industrial/commercial land use. The nighttime cooling effect expanded to the surrounding area and induced cooling of between 0.5°C and 1.2°C in the area around the park’s borders. Coutts et al. (2008) developed a modified air-pollution model to assess the impact of urban planning on local climate. They also estimated the UHII in Melbourne in the present day and the 2030s using the modified air-pollution model. Their results indicated that the maximum intensity of the UHII in the 2030s would not increase from that of the present-day urban area but that high-temperature areas were projected to expand. In their study, they demonstrated that regional urban modeling is a powerful tool for evaluating the climatological effects of various urban scenarios and that the results from the model are likely to be valuable to urban planners, as also has been reported in previous studies (e.g., Manins 1995).

Previous studies have indicated changes in the UHII that are due to historical urbanization, different urban planning scenarios, and the cooling effects of greening the city. Most of these studies implicitly assume a population change in association with land-use change, and most permit large-scale alteration of land use. Large-scale alterations are very difficult to undertake in high-density urban areas such as the TMA, however. In addition, to determine the appropriate urban form to counter an uncomfortable thermal environment, it is necessary to assess the urban scenarios from the perspective of inhabitants. This study uses the current urban situation and two projected urban scenarios with the same population as the current urban situation: the dispersed-city and compact-city scenarios. The levels of social and economic activity in the two projected scenarios are assumed to remain unchanged. The model then investigates how differences in the urban form moderate nighttime thermal conditions in the TMA from the perspective of inhabitants as well as from a climatological perspective.

The model setting and urban scenarios are described in sections 2 and 3. Section 4 presents the results in terms of the impacts of different urban forms on thermal conditions in the TMA. In section 5, the differences in urban form are discussed from the perspective of an adaptation strategy to global warming in urban areas. Section 6 provides the conclusions and further remarks.
2. Model descriptions

The numerical model used in this study was the Weather Research and Forecasting Model, version 3.1.1 (hereinafter WRF; Skamarock et al. 2008). The model was used to calculate meteorological conditions in the TMA during August of 2010. The model domains are a nested system with three grids. The outermost, middle, and inner domains are covered by 162 $\times$ 150, 251 $\times$ 231, and 203 $\times$ 201 grid cells with horizontal spatial resolutions of 20, 4, and 2 km, respectively (Fig. 1a). A total of 31 vertical model levels were used, and the height of the lowest level was set at approximately 30 m above ground level. The initial and boundary conditions for WRF were provided from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data (Kalnay et al. 1996). The simulation period was from 25 July to 1 September 2010, and the results for August were used for analysis.

The WRF–Urban Canopy Model (UCM) was modified to incorporate the gridded urban fraction and the gridded sensible and latent anthropogenic heat fluxes in the single-layer UCM. In the original WRF, land-use type in a grid cell is defined by the most dominant land-use category in the grid cell. Urban areas in the model are limited to densely urbanized areas. A vegetation type in an urban area is fixed to one type of vegetation that is arbitrarily defined in a parameter table. In this study, all grid cells had two kinds of land-use subtiles: one was urban and the other was the most dominant land use in a grid cell, excluding urban (hereinafter LU_dom). The heat and moisture fluxes from each grid cell were calculated from an area-weighted average of the fluxes from the two subtiles in the grid cell (Chen et al. 2011), as shown in Eq. (A6) of appendix A, below. These fluxes were calculated by the UCM for urban tiles and by the “Noah” land surface model for other land-use tiles. The method used to diagnostically estimate surface air temperature at 2 m was also modified, as described in appendix A. Table 1 lists the other settings of the physical scheme options.

Observed data from a series of Automated Meteorological Data Acquisition Systems (AMeDAS) were used to evaluate the model performance. There are 57 AMeDAS stations located at altitudes lower than 200 m above sea level in the TMA (Fig. 1b).

3. Urban scenarios and experimental design

a. Urban parameters for the current urban scenario

This study assumed a current urban scenario and two other urban scenarios, the dispersed-city and compact-city scenarios, which were introduced by Yamagata et al. (2011) to estimate the moderation of the urban heat island by differences in urban form. The land-use data for the current urban scenario were classified into seven categories as follows: forest, cropland, paddy, grassland, bare, water area, and urban. Each land-use category was
estimated by applying the improved subspace method (Bagan and Yamagata 2010) using Landsat images and is presented as the fraction of data on a 1-km square mesh. The fractions of urban and LU_dom in a model grid cell were calculated from the 1-km mesh fraction (Fig. 2a).

The sensible and latent anthropogenic heat fluxes (AH) for the current urban scenario were estimated as follows: 1) The AH from residential and commercial buildings was calculated by multiplying the floor area by the AH consumption rate per unit area for each building type reported in Fukami et al. (2003). The floor-area dataset was created on the basis of reported fixed-asset tax rolls (FATR) published by the Ministry of Internal Affairs and Communications (MIC) in 2005. 2) The AH from road transport was calculated from carbon dioxide (CO₂) emission data from road transport (Kannari et al. 2007), CO₂ emission coefficients, and the calorific value of gasoline (Ministry of the Environment 2012). 3) The total number of AH data per 1-km mesh cell was obtained as the sum of AH from buildings and transport. The diurnal variations in sensible and latent AH emissions were based on values for August reported in National Institute for Resources and Environment (1997), as shown in Fig. 3. The diurnal cycle was assumed to be horizontally uniform in this study, although it is likely to be spatially inhomogeneous. The number of building levels averaged in a grid cell was calculated by dividing floor area by land area, and the floor-area and land-area data were obtained from the FATR report. The building level was used only to define the urban category for each grid cell in this study because it is difficult to estimate the building height, roof width, and road width for each grid cell even though they are important parameters for the UCM. Areas with building levels of eight floors or more and fewer than four floors were defined as urban categories UC1 and UC3, respectively, and the other areas were defined as UC2 (Fig. 4). The urban parameters except for the urban fraction and AH were given specific values according to the urban category in each grid cell, as shown in Table 2. The population data, provided by the national population census in 2005 and published by the MIC, were used to determine the nighttime population density in the current urban scenario. The maps of urban fraction, daily mean AH, and population for the current urban scenario are shown in Figs. 2a, 2f, and 2k, respectively. The urban area was distributed along the railway. A larger AH was determined closer to the central area.

b. Urban scenarios for the dispersed city and compact city

The dispersed-city and compact-city scenarios were produced using a spatially explicit land-use model (Yamagata et al. 2011). The model is a land-use equilibrium model entirely based on urban economic theory. The land-use model considers three different agents (i.e., households, developers, and absentee landlords) and determines the location of housing to maintain a balance between utility maximization for households and profit maximization by developers and absentee landlords. Therefore, the distribution of residential buildings changes depending on the demand for land and housing under given conditions, whereas the distribution of offices and commercial buildings is fixed to that of the current urban situation. The details of this spatially explicit land-use model are described in Yamagata and Seya (2013) and Yamagata et al. (2013). To show the possible range of changes in the urban form in the TMA, the following conditions were assumed in the land-use model. The strategy for the dispersed-city scenario was automobile dependent and included 1) free purchase costs for a car, 2) no fuel cost for a car, and 3) toll-free expressways. Alternatively, the compact-city scenario assumed 1) a reduction in the land available for residential buildings in areas more than 1 km away from train stations and 2) the prohibition of car use.

The urban fractions in the dispersed-city and compact-city scenarios were determined by the land-use model according to the above assumptions. The increased/decreased portion in the urban area was balanced by changing the LU_dom area in a grid cell. The distributions

<table>
<thead>
<tr>
<th>Physical options</th>
<th>Schemes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud microphysics</td>
<td>WRF single-moment 6-class graupel scheme</td>
</tr>
<tr>
<td>Convective parameterization</td>
<td>Kain–Fritsch (new Eta) scheme</td>
</tr>
<tr>
<td>Radiation scheme</td>
<td>Rapid Radiative Transfer Model (GCM application version) radiation scheme</td>
</tr>
<tr>
<td>Boundary layer</td>
<td>Mellor–Yamada–Janjic turbulent kinetic energy scheme</td>
</tr>
<tr>
<td>Surface layer</td>
<td>Monin–Obukhov (Janjic) scheme</td>
</tr>
<tr>
<td>Land surface model</td>
<td>Noah land surface model (Chen and Dudhia 2001)</td>
</tr>
<tr>
<td>Urban model</td>
<td>Single-layer UCM (Kusaka et al. 2001)</td>
</tr>
</tbody>
</table>
Fig. 2. Distribution of urban parameters: (a)–(c) urban-area ratio, (f)–(h) daily mean anthropogenic heat emission (W m$^{-2}$), and (k)–(m) population per square kilometer in the (left) current urban situation, (center) dispersed-city scenario, and (right) compact-city scenario. Differences in the urban-area ratio and anthropogenic heat flux from the current urban situation are shown in (d) and (i), respectively, for the dispersed-city scenario and in (e) and (j), respectively, for the compact-city scenario.
of AH and population were estimated in accordance with the increase or decrease in households. Previous studies have reported that AH varies depending on outside air temperature, as a result of a positive feedback between air temperature and air-conditioning energy demand (e.g., Kikegawa et al. 2003). This feedback was not considered in this study, however. Changes in AH emission from buildings in the two urban scenarios were only dependent on the changes in floor area relative to the current situation. The urban category was defined according to the number of building levels, calculated in the same way as in the current urban situation using the modified floor and land areas. The distribution of the urban category in the dispersed-city and compact-city scenarios was almost the same as in the current urban situation (not shown in the figures). The ratios of building height to road width in the dispersed-city and compact-city scenarios were assumed to be the same as in the current urban situation. The distributions of urban parameters in the two urban scenarios are illustrated in Fig. 2. The residential area expands to the suburbs, with a lower cost of commuting in the dispersed city (Figs. 2b,d). The AH also increases in suburban areas because of frequent car use and the expansion of residential areas. In contrast, the pattern of the urban distribution in the compact city is similar to the current urban situation (Fig. 2c), and the AH is enhanced in the central part of the TMA because of the concentration of people and the increase in floor area in that area (Figs. 2h,j).

c. Experimental design

The numerical experiments listed in Table 3 were conducted to evaluate the effect of moderation of the urban form on the urban heat island. The simulation CTL_o was a control simulation for 2010 using the current urban situation. URB_d and URB_c were simulations to estimate the impact of changes in the urban form on urban climate. These simulations were otherwise the same as CTL_o, but land use, AH, and urban category were different from the current urban situation and represented the dispersed-city and compact-city scenarios, respectively. In addition, sensitivity experiments were conducted to estimate the contribution of anthropogenic heat emissions and land-use changes to changes in surface air temperature. The CTL_o_noAH, URB_d_noAH, and URB_c_noAH simulations used the same settings as CTL_o, URB_d, and URB_c but without the AH emission. The contributions of land-use changes were obtained from the differences between URB_d_noAH or URB_c_noAH and CTL_o_noAH. The contributions of

![Figure 3](image1.png)

**Fig. 3.** Diurnal cycle of sensible and latent anthropogenic heat emissions. The value indicates the multiplication coefficient applied to the daily average heat emissions shown in Fig. 2.

![Figure 4](image2.png)

**Fig. 4.** Distribution of the urban category defined by the building levels in the current urban situation.

![Table 2](table1.png)

**Table 2.** Urban parameters for each urban category. The urban category in a grid cell is defined by the gridded building levels in the grid cell. The grid cells with building levels ≥ 8 floors and < 4 floors were defined as UC1 and UC3, respectively, and the other areas were defined as UC2.

<table>
<thead>
<tr>
<th>Urban category</th>
<th>UC1</th>
<th>UC2</th>
<th>UC3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building height used in UCM (m)</td>
<td>16</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>Roof width used in UCM (m)</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Road width used in UCM (m)</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Sky-view factor</td>
<td>0.3</td>
<td>0.45</td>
<td>0.65</td>
</tr>
<tr>
<td>Displacement height (m)</td>
<td>4.8</td>
<td>3</td>
<td>1.8</td>
</tr>
<tr>
<td>Roughness length for momentum (m)</td>
<td>2.4</td>
<td>1.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Roughness length for heat (m)</td>
<td>0.24</td>
<td>0.15</td>
<td>0.09</td>
</tr>
<tr>
<td>Building heat conductivity (J m$^{-1}$ s$^{-1}$ K$^{-1}$)</td>
<td>2.28</td>
<td>2.28</td>
<td>2.28</td>
</tr>
<tr>
<td>Emissivity</td>
<td>0.97</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td>Surface albedo of roof/wall/ground</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>
the differences in AH were estimated from the difference in the AH impact on surface air temperature between the two scenarios and the current urban scenario. The AH impact for each scenario was obtained from the difference between the simulations with and without AH under the corresponding urban scenario.

4. Results

The control simulation (CTL_o) was compared with observations to validate the model. The observed monthly-mean nighttime surface air temperature between 0100 and 0500 Japan standard time (JST) (hereinafter, nighttime temperature) in August is shown in Fig. 5a. The temperature in the central part of the TMA exceeded 27°C. Areas with high temperatures (>26°C) were found in Tokyo and the eastern parts of Kanagawa, Saitama, and Gunma prefectures. These areas all have a higher urban-area ratio (shown in Fig. 2a). Compared with these areas, the eastern parts of the TMA, Ibaraki, and Chiba prefectures displayed relatively lower surface air temperatures because of the limited urban area. The nighttime temperature simulated in CTL_o agreed well with the observations (Fig. 5b). The mean bias of nighttime temperature averaged over the 57 observation points was 0.07°C, and the root-mean-square error (RMSE) was 0.85°C. The temperature in Chiba and Ibaraki was underestimated by about 1°C. The reason for this temperature underestimation was related to the underestimation of the number of small settlements in mountainous regions in the urban-fraction data, especially in the southern part of Chiba (not shown in the figure). The simulated magnitude of the nighttime wind speed also agreed well with the observation. The mean

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**Table 3. Experimental design.**

<table>
<thead>
<tr>
<th>Run name</th>
<th>Expt description</th>
<th>Boundary data</th>
<th>Land use</th>
<th>AH</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTL_o</td>
<td>Hindcast simulation</td>
<td>NCEP–NCAR reanalysis data in 2010</td>
<td>Current urban situation (original)</td>
<td>AH of current urban situation</td>
</tr>
<tr>
<td>URB_d</td>
<td>Impact of urban scenario</td>
<td>NCEP–NCAR reanalysis data in 2010</td>
<td>Dispersed-city scenario</td>
<td>AH of dispersed-city scenario</td>
</tr>
<tr>
<td>URB_c</td>
<td>Impact of urban scenario</td>
<td>NCEP–NCAR reanalysis data in 2010</td>
<td>Compact-city scenario</td>
<td>AH of compact-city scenario</td>
</tr>
<tr>
<td>CTL_o_noAH</td>
<td>Sensitivity experiment</td>
<td>NCEP–NCAR reanalysis data in 2010</td>
<td>Current urban situation (original)</td>
<td>0</td>
</tr>
<tr>
<td>URB_d_noAH</td>
<td>Sensitivity experiment</td>
<td>NCEP–NCAR reanalysis data in 2010</td>
<td>Dispersed-city scenario</td>
<td>0</td>
</tr>
<tr>
<td>URB_c_noAH</td>
<td>Sensitivity experiment</td>
<td>NCEP–NCAR reanalysis data in 2010</td>
<td>Compact-city scenario</td>
<td>0</td>
</tr>
</tbody>
</table>

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**Fig. 5.** Distribution of monthly nighttime surface air temperatures averaged between 0100 and 0500 JST in August 2010: (a) observed data and (b) model results for the CTL_o simulation. The gray color in (a) illustrates the topography, which is the same as that shown in Fig. 1b.
The bias of wind speed averaged over all of the observation points was 0.86 m s\(^{-1}\), and the RMSE was 1.17 m s\(^{-1}\).

The changes in nighttime temperature due to modification of the urban form are indicated in Fig. 6. A surface air temperature increase was predicted throughout most of the TMA in the URB\(_d\), with the exception of the central part (Fig. 6a). Warming of more than 0.6\(^\circ\)C was simulated in the Chiba and Ibaraki prefectures because of the large expansion of urban area in the region (as shown in Fig. 2d). The developed urban area in Tokyo, Kanagawa, and Saitama was projected to experience at most about a 0.3\(^\circ\)C temperature increase. In the central part of Tokyo, however, nighttime temperature was projected to decrease by about 0.1\(^\circ\)C.

The change in area-averaged nighttime temperature over the TMA is illustrated in Fig. 7. In the URB\(_d\) simulation, a temperature increase of 0.34\(^\circ\)C was projected. Of this increase, 0.31\(^\circ\)C was caused by land-use changes and 0.03\(^\circ\)C was derived from the increase in AH. Therefore, the temperature increase in the dispersed-city scenario was mainly attributed to land-use changes associated with urban expansion. The influence of AH was also not negligible because it generated a 12% enhancement in the effect of AH on surface air temperature relative to the current urban situation.

In the URB\(_c\) simulation, the response of nighttime temperatures to changes in the urban form was opposite that projected in the URB\(_d\) simulation. The nighttime temperature was reduced by about 0.1\(^\circ\)C over a large area of the TMA, except for the central part, where the temperature increased by about 0.1\(^\circ\)C (Fig. 6b). The area-averaged surface air temperature decreased by \(\sim 0.09\)^\(\circ\)C because of the concentration of urban area (Fig. 7). The impact of the reduction of AH on the change in nighttime temperature was \(\sim 0.03\)^\(\circ\)C, which was almost the same amplitude as projected in URB\(_d\). These results indicate that the compact-city scenario had the potential to reduce the intensity of the urban heat island in the whole of the TMA.
To clarify the causes of surface air temperature changes in detail, the changes in surface skin temperature and energy budget at Ryugasaki and Tokyo are shown in Fig. 8. These locations are a rural area and a central area, respectively, as shown in Fig. 1b. The illustrated values of temperature and fluxes are averaged in nine grid cells centered on the nearest grid cell from each AMeDAS station. The urban-area ratio at Ryugasaki increased from 0.197 in the current situation to 0.249 in the dispersed-city scenario and decreased to 0.187 in the compact-city scenario, whereas in Tokyo it changed from 0.826 to 0.809 in the dispersed-city scenario and 0.828 in the compact-city scenario. The reason for the small change in the urban ratio between the current urban and the compact-city scenario in Tokyo is that the urban area expanded vertically in the central area.

The upward latent heat flux is greater than the sensible heat flux in the daytime in Ryugasaki, because the
The urban area is limited and irrigated cropland and pasture dominate in the current urban situation (Fig. 8c). During the night, the ground heat flux is negative as a result of the conduction of heat from the warm ground to the cooler surface. The release of stored heat as longwave radiation results in a cooling of the ground surface. Figures 8e and 8g display the differences in the fluxes between the current urban and the dispersed-city or compact-city scenarios, respectively. In the dispersed-city scenario, the nighttime surface temperature was projected to increase by approximately 0.54°C in Ryugasaki (Fig. 8a). The sensible and latent heat fluxes increased slightly during the night as a result of the increase in anthropogenic heat emissions. The released ground heat flux was enhanced during the night with the increase in surface temperature. The surface temperature was higher than for the current urban situation during the night, however, because of the increased heat storage associated with the expansion of the urban area. Therefore, the reduced effect of radiative cooling induces the elevation of nighttime surface air temperature in the dispersed-city scenario in addition to the increase of anthropogenic sensible heat emissions. In contrast, the surface temperature in Tokyo was projected to rise by approximately 0.38°C in the compact-city scenario (Fig. 8b). The changes in the latent heat flux and the ground heat flux were minimal during the night (Fig. 8h). Therefore, the increase in surface air temperature was mainly due to the growth of anthropogenic heat fluxes in Tokyo in the compact-city scenario (Fig. 8h).

The reduction in nighttime temperature is important in terms of sleep disruption and heatstroke. The compact-city scenario resulted in a reduced nighttime temperature in the TMA, as shown in Figs. 6 and 7. On the other hand, nighttime temperature increased in the central part of the TMA, which has a very dense population. Figure 9 shows the population in different areas classified by temperature category, as defined by the monthly mean of daily minimum nighttime temperature (Tminave). The daily minimum nighttime temperature was defined as the minimum temperature between 0100 JST and 0500 JST. The population in each temperature category from I to IX was calculated by summing the population in the grid cells that met the conditions of Tminave.

In Tokyo, the diurnal variations of heat fluxes displayed characteristics typical of an urban area. The sensible heat flux prevailed throughout the day over the latent heat flux, and the amplitude of the ground heat flux was larger than in a rural area (Fig. 8d). In the dispersed-city scenario, the nighttime surface temperature was projected to reduce by approximately 0.4°C in Tokyo (Fig. 8b). The main cause of the temperature reduction was a decrease in anthropogenic sensible heat emission by approximately 13 W m⁻², although several changes occurred in the ground heat flux of about 3 W m⁻² (Fig. 8f). In contrast, the surface temperature in Tokyo was projected to rise by approximately 0.38°C in the compact-city scenario (Fig. 8b). The changes in the latent heat flux and the ground heat flux were minimal during the night (Fig. 8h). Therefore, the increase in surface air temperature was mainly due to the growth of anthropogenic heat fluxes in Tokyo in the compact-city scenario (Fig. 8h).

The reduction in nighttime temperature is important in terms of sleep disruption and heatstroke. The compact-city scenario resulted in a reduced nighttime temperature in the TMA, as shown in Figs. 6 and 7. On the other hand, nighttime temperature increased in the central part of the TMA, which has a very dense population. Figure 9 shows the population in different areas classified by temperature category, as defined by the monthly mean of daily minimum nighttime temperature (Tminave). The daily minimum nighttime temperature was defined as the minimum temperature between 0100 JST and 0500 JST. The population in each temperature category from I to IX was calculated by summing the population in the grid cells that met the conditions of Tminave.
simulations. Conversely, the population decreased in the higher temperature categories (II and III) when compared with that in the current urban situation. This resulted in a tendency for nighttime temperatures affecting citizens to improve in both urban scenarios. This happened because either people would move into the surrounding areas (region iii in Fig. 1b) where temperatures were lower in the dispersed-city scenario, or the nighttime temperature would be reduced throughout much of the TMA in the compact-city scenario, as shown in Fig. 6b. Note, however, that the population increased by about one million in the highest temperature category (I) in the URB_c simulation. Most people in category I live in the central area of the TMA (i.e., region i). This resulted in further deterioration in nighttime thermal conditions in the central part of the TMA in the compact-city scenario.

5. Discussion

Moderation of the urban-heat-island effect is likely to become an adaptation to global warming. In addition, it is important to reduce the emission of greenhouse gases so as to mitigate future global warming. Urban areas contribute 67% of global energy consumption and 71% of global CO₂ emissions (International Energy Agency 2008). One of the advantages of the compact urban form is the efficiency of energy use that results from down-sizing the city area and increasing the active use of public transportation systems (Newman and Kenworthy 1999; Taniguchi et al. 2008; Nakamichi et al. 2012).

The change in per capita CO₂ emission when compared with the current situation is shown in Fig. 10a. The method used to calculate CO₂ emissions for each urban scenario is described in appendix B. The per capita CO₂ emission is 242 kg CO₂ per month in the TMA in the current urban situation. The emission increased by about 80 kg CO₂ in the dispersed-city scenario, corresponding to a level about 1.3 times that in the current urban situation. This is because of the increase in energy use associated with the expansion of floor area and aggressive vehicle use. In contrast, the CO₂ emission in the compact-city scenario slightly decreased when compared with the current urban situation, despite the fact that the efficiency of energy consumption per unit area was not considered in this study. Therefore, the compact-city scenario with lower energy consumption seems more likely to mitigate the effects of global warming than does the dispersed-city scenario, although the reduction in CO₂ emissions was very small in the TMA (Fig. 10a). The reason for the small reduction in CO₂ emissions in the compact-city scenario seems to be that the TMA developed along the railroad lines and already had some features of a compact city.

The monthly-mean daily minimum surface air temperature (Tminave) increased in the central area as a result of the high population density in the compact-urban scenario, as shown in Figs. 6b and 9. The nighttime thermal environment deteriorated further in the central area (Fig. 10b). This finding suggests that the adoption of a compact-city strategy alone may not always reduce the increase in temperature due to global warming in densely urbanized areas such as the TMA, although it is appropriate for the mitigation of global climate change from the perspective of energy consumption.

6. Conclusions and remarks

This study investigated the moderation of nighttime surface air temperatures in the TMA through simulations of dispersed-city and compact-city scenarios at the current population level. The area-averaged nighttime
temperature in the TMA increased by about 0.34°C in the dispersed-city scenario and decreased by about 0.1°C in the compact-city scenario when compared with the current urban situation. The area-averaged thermal environment during the night tended to deteriorate in the dispersed-city scenario and to improve in the compact-city scenario. In contrast, each urban scenario had the opposite impact on the nighttime surface air temperature in the central part of the TMA, with a temperature increase in the compact-city scenario and a decrease in the dispersed-city scenario. As a result, the number of people living in the area with higher nighttime temperatures (more than 27.8°C) increased by about one million in the compact-city scenario when compared with the current urban situation. Therefore, the severe high-temperature conditions worsened in the city center in the compact-city scenario.

The adoption of a compact-city scenario is expected not only to moderate the urban-heat-island effect but also to act as an adaptation strategy for global warming in urban areas because it would reduce energy consumption through more frequent use of public transport systems and efficient energy use. The results of this study suggest that the compact-city scenario is not always appropriate for the moderation of the urban heat island, however, especially in the central part of the TMA. To avoid a deterioration of the thermal environment in the central area, the temperature increase needs to be compensated for by other strategies, such as the greening of urban areas. In combination with other strategies, a compact city has the potential to be useful not only as an adaptation to the higher temperatures associated with global warming in the urban area but also as an overall mitigation technique for global warming as a result of reducing greenhouse-gas emissions. This study indicates that it is important to evaluate an adaptation plan for higher urban temperatures from several perspectives, that is, not only taking climatological aspects into consideration but also its impacts on urban inhabitants.

The aggravation of thermal conditions estimated in this study is likely to be underestimated in the central part of a city in the compact-city scenario because the growth of energy demand for air conditioning, due to the increased nighttime temperature, was not considered. The further concentration of the urban area into the city center leads to the verticalization of buildings in the compact-city scenario. The wind and temperature fields are affected by the increased roughness length and the enhanced shield effect of radiation as a result of the vertical extension of building height. Further research is required to evaluate these effects, because they were not directly addressed in this study.

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APPENDIX A

Method for the Diagnostic Calculation of Surface Air Temperature at 2 m

The method for estimating surface air temperature at 2 m above ground level was modified from the original method in WRF V3.1.1 as follows. The surface air temperature at 2 m was estimated diagnostically from air temperature at the first atmospheric model level by assuming the Monin–Obukhov similarity theory. The dimensionless potential temperature gradient is expressed as (e.g., Arya 2001)

$$\left( \frac{kz}{\theta_0} \right) \left( \frac{\partial \theta}{\partial z} \right) = \phi_h \left( \frac{z}{L} \right),$$

(A1)

where $k$ is the von Kármán constant (=0.4), $L$ is the Obukhov length, $\theta_0$ is the temperature scale, and $\phi_h$ is the basic universal similarity function. The temperature profile is written by integrating Eq. (A1) with respect to height as

$$\theta - \theta_0 = \left( \frac{\theta_0}{k} \right) \left[ \ln \left( \frac{z + z_0}{z_0} \right) - \phi_h \left( \frac{z}{L} \right) \right],$$

(A2)

where $z_0$ is the roughness length, $\theta_0$ is the extrapolated temperature at the height of $z_T$, and $\phi_h$ is the integrated similarity function for heat related to $\phi_h$ as

$$\phi_h \left( \frac{z}{L} \right) = \int_{z_0/L}^{(z + z_0)/L} \left[ 1 - \phi_h (\xi) \right] \frac{d\xi}{\xi},$$

(A3)

where $\xi = z/L$. To determine the $\phi_h$ function, the empirical forms of $\phi_h$ given below were used to simplify the process, although more suitable similarity functions were recently discussed in Jiménez et al. (2012):

$$\phi_h = (1 - 16\xi)^{-1/2}, \quad \text{for unstable conditions} \ (\xi < 0),$$

$$\phi_h = (1 + 7\xi), \quad \text{for stable conditions} \ (0 \leq \xi),$$

(A4)
Corresponding to Eq. (A3) and (A4), the integrated similarity function for heat was obtained as

$$\psi_h = \ln \frac{z}{z_T} + 2 \ln \frac{y_T + 1}{y + 1},$$

for unstable conditions, and

$$\psi_h = -7 \frac{z}{L},$$

for stable conditions,

where $y = (1 - 16 \zeta_T)^{1/2}$, $y_T = (1 - 16 \zeta_T)^{1/2}$, and $\zeta_T = z_T/L$.

The temperature at $2 \text{ m}$ used for analysis was di-

$$2 \text{ m} = \theta_2 + \left( \frac{\theta_a}{k} \right) \left[ \ln \left( \frac{2 + z_o}{z_0} \right) - \psi_h \left( \frac{2}{L} \right) \right]$$

$$- \left[ \ln \left( \frac{z_o + z_T}{z_0} \right) - \psi_h \left( \frac{z_T}{L} \right) \right],$$

(A5)

where $z_o$ is the first model level. The Obukhov length, defined as $L = u^2_o \theta_a/(kg \theta_e)$, and the temperature scale, defined as $\theta_e = -H/(\rho_o c_p u_a)$, were obtained from the grid average of the sensible heat flux $H$ and the friction velocity $u_a$ in a grid cell, $\rho_o$ is density at $z = z_o$, and $c_p$ is the specific heat of air at constant pressure. The grid averages of $H$ and $u_a$ were obtained as follows (Chen et al. 2011):

$$H = F_{urb} H_{urb} + F_{veg} H_{veg} \quad \text{and} \quad (A6)$$

$$u_a = (F_{urb} u^2_{urb} + F_{veg} u^2_{veg})^{1/2},$$

(A7)

where $F_{urb}$ and $F_{veg}$ are the fractional coverage of urban and dominant land use except for urban (LU_dom), respectively. Also, $H_{urb}$ and $u_{aurb}$ are the sensible heat flux and the friction velocity for the subtile of urban, while $H_{veg}$ and $u_{aveg}$ represent the subtile of LU_dom.

### APPENDIX B

#### The Procedure for Calculating CO2 Emissions

The monthly CO2 emissions were calculated from the anthropogenic heat emission data as follows. In the calculation, the energy coefficient and energy allocation of energy sources were assumed to remain unchanged in the different urban scenarios. The CO2 emissions (kg CO2 m$^{-2}$) from transportation were calculated as

$$\text{CO2 emission from transport} = EC \times AH \text{ from transport} \times T / HV.$$

The AH from transport (W m$^{-2}$) was available for each grid cell. Here, $T$ is the number of seconds in a month ($60 \times 60 \times 24 \times 31$). The values for gasoline shown in Table B1 (Ministry of the Environment 2012) were used for the heating value HV (J L$^{-1}$) and CO2 emission coefficient EC (kg CO2 L$^{-1}$).

The CO2 emissions from residential and commercial buildings were obtained by summing the CO2 emissions from four main energy sources: electricity, city gas, heating oil, and liquefied petroleum gas (LPG). The CO2 emissions from each energy source were calculated using the proportion of each energy source in the final energy consumption and the CO2 emission coefficient for each energy source. The proportion of each energy source in the final energy consumption (Ratio) was applied to the value in the TMA (Agency for Natural Resources and Energy 2012):

$$\text{CO2 emission from buildings} = \sum_{i=1}^{4} (EC_i \times AH \text{ from buildings} \times \text{Ratio}_i \times T / HV_i).$$

For HV and EC, the values reported in Ministry of the Environment (2012) were used except for the HV value for electricity, which was taken from Kainou (2012). The total CO2 emissions in the TMA were calculated from the emissions from transportation and buildings.
REFERENCES


