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(Manuscript received 12 October 2005, in final form 26 April 2006)

ABSTRACT

A coupled model consisting of a multilayer urban canopy model and a building energy analysis model has been developed to investigate the diurnal variations of outdoor air temperature in the office areas of Tokyo, Japan. Observations and numerical experiments have been performed for the two office areas in Tokyo. The main results obtained in this study are as follows. The coupled model has accurately simulated the air temperature for a weekday case in which released waste heat has been calculated from the energy consumption and cooling load in the buildings. The model has also simulated the air temperature for a holiday case. However, the waste heat from the buildings has little influence on the outdoor temperatures and can be neglected because of the low working activity in the buildings. The waste heat from the air conditioners has caused a temperature rise of 1°–2°C or more on weekdays in the Tokyo office areas. This heating promotes the heat-island phenomenon in Tokyo on weekdays. Thus, it is shown that the energy consumption process (mainly with air conditioning) in buildings should be included in the modeling of summertime air temperature on weekdays in urban areas.

1. Introduction

Air temperature in urban areas is strongly affected by morphology, surface materials, and the anthropogenic heat emitted from automobiles and buildings (e.g., Oke 1988; Grimmond 1992; Grimmond and Oke 1999; Fan and Sailor 2005). In office areas in the big cities of Asian countries, this “waste” heat from air conditioners into the urban atmosphere is significant, especially during summer. In the office areas of Chiyoda and Chuo Wards in the Tokyo metropolitan area in Japan, the waste heat resulting from the air-conditioning operation is more than one-half of the sensible heat from the surface during the summer (Center for Environmental Information Science 2000). In Tokyo, the urban air temperature in summer season correlates well with energy consumption in the buildings. About 1.6 GW of new electricity demand, which is equivalent to the electricity generated by one and one-
half nuclear power plants, is required in the greater Tokyo area as the daily maximum temperature increases by 1.0°C (Sakai and Nakamura 1999). These facts suggest that waste heat from buildings also affects air temperatures in urban areas.

In mesoscale meteorological models with a slab type of urban model, the waste heat was compulsorily added to the terms in the surface heat-budget equation or directly discharged at lower atmospheric layers as heat sources (e.g., Ichinose et al. 1999; Taha 1999; Fan and Sailor 2005). The waste heat data used in the model were sometimes calculated from the total energy consumption at each grid in the urban area (e.g., Ichinose et al. 1999; Kanda et al. 2001).

To account for interactions between urban meteorological fields and waste heat from buildings, models that calculate the building energy consumption (i.e., electricity and town gas) and waste heat from air conditioners have been incorporated into the urban canopy models (Ashie et al. 2001; Kondo and Kikegawa 2003). Such models can be used to predict the effectiveness of countermeasures against the heat island (e.g., green coverage on the building surface, reduction of waste heat); the models also have been used to investigate the extent to which energy-saving systems (e.g., cogeneration system, natural energy system) can affect urban temperatures (Taha et al. 1988; Kikegawa et al. 2003; Krayenhoff et al. 2003). However, the validation of the model results are not always enough because 1) as a result of the heterogeneity of urban temperature distribution a large number of temperature measurements are required for comparison with the model simulations and 2) it is difficult to measure directly the influence of waste heat from air conditioners under the urban thermal environment.

Kondo and Kikegawa (2003), and Kikegawa et al. (2003) compared a calculated air temperature with a temperature measured at only one point in Tokyo. Because the grid-averaged temperature was predicted by the model, the temperature used for the comparison should be measured at many points in a grid area and averaged before comparing with model results. Kondo et al. (2005) subsequently measured air temperature at six points in a grid area and compared those values with the calculated temperature.

As mentioned before, some researchers simulated the urban meteorological fields using a mesoscale meteorological model with implicit building effects (e.g., Martilli et al. 2002; Dupont et al. 2004). Other studies used a mesoscale model with a single-layer urban canopy model (e.g., Lemonsu and Masson 2002; Kusaka and Kimura 2004a,b). However, there are few studies with a multilayer urban canopy model that explicitly treats the buildings, except for those of Kondo and Kikegawa (2003), Kikegawa et al. (2003), and Kondo et al. (2005). Furthermore, there is no study in which detailed comparisons between the simulated results and the observations at many sites in a small area (i.e., one grid cell of the model) within a real gigantic city were conducted.

Fujibe (1987) used 25 yr of temperature measurements to show that the measured air temperature was lower on Sundays (i.e., holidays) than on weekdays during daytime in the central part of Tokyo. In an office area, the waste heat from buildings increases the urban air temperature more during weekdays when more people are working in the office. Kondo et al. (2005) verified the performance of a multilayer urban canopy model without waste heat from buildings for a holiday period and stated that the inclusion of a building energy consumption model in the urban canopy model is also required to verify the results for weekdays in future studies.

In this paper, a building energy consumption model is coupled with a multilayer urban canopy model to simulate air temperatures on weekdays and on holidays and to determine whether worker activities within buildings (i.e., air-conditioning operations) should be calculated in the model. Furthermore, to validate the model, the model results are compared with observational results at many points in two model grids that represent office areas in Tokyo. Using the obtained results, the influence of air-conditioning waste heat on urban air temperature will be quantitatively clarified.

2. Model

The coupled model used here consists of an urban canopy meteorological model (CM) and a building energy analysis model (BEM).

The multilayer CM that was developed by Kondo and Liu (1998) and improved by Kondo et al. (2005) is used in this study. The general features of the model are shown in Fig. 1. This numerical model calculates meteorological elements such as wind speed, air temperature, and humidity within urban street canyons, the entire scale of which is several hundred meters. The buildings are assumed to be rectangular parallelepipeds of various heights with the same width. In the form-drag calculations, the floor density of buildings $P_b(z)$ is assumed to have a vertical distribution. Here floor density means the ratio of the buildings that occupy level $z$ to all of the buildings $[0 \leq P_b(z) \leq 1]$. The computational domain is vertically divided into multiple layers, and the vertical distributions of the horizontal wind speed ($u$ and $v$ components), temperature, and humidity are predicted by vertically one-dimensional prog-
nostic equations. The basic equations and physics of the CM are summarized in the appendix.

To estimate the waste heat from air conditioners, we used the BEM (Kikegawa et al. 2003). Details of the building heat budget in the BEM are illustrated in Fig. 2. The BEM is a numerical model that calculates the heat exchange between the urban canopy atmosphere and the energy system in the buildings. This model aims to reproduce the time variation of the waste heat from air-conditioning systems, which results from the response of cooling load inside the buildings to the urban meteorological fields. The cooling load is calculated through a heat-budget equation in the building room, which is assumed to consist of one box in a building. The equations and physics of the BEM are also described in the appendix.

3. Observations

a. Observation locations and meteorological conditions

The air and road-surface temperatures at a number of points in two urban areas with office buildings are measured 1) to compare with the results calculated by the coupled CM–BEM model and 2) to investigate the temporal and spatial variations of the air temperatures throughout the day. Both observation areas are located in the center of the Tokyo metropolitan area (Fig. 3a). The Kanda area, which mainly consists of office buildings, is near the imperial palace, and the Tokyo district meteorological observatory is located about 300 m south of the area. The Nihonbashi area is 1.5 km southeast of the Kanda area and also consists of office buildings.

The observations were made during 29–30 July and 10–11 August 2002. The Japan islands were covered by high pressure on both periods. It was cloudy in the Tokyo metropolitan area from the afternoon of 28 July to the morning of 29 July, and it became fair on 30 July. There was cloudless, clear weather on 10–11 August. The two days 29 and 30 July were weekdays, whereas 10–11 August were the beginning of the traditional Japanese summer holidays. Hereinafter, observations during the period of 29–30 July 2002 are called the “weekday” observation, whereas those of 10–11 August 2002 are called the “holiday” observation. Kondo et al. (2005) used these holiday observation data of the Kanda area to verify only CM performance. However, the study reported in this paper used many data measured at both the Kanda and Nihonbashi areas during both weekday and holiday periods to verify the coupled CM–BEM performance. Figure 4 shows the meteorological data measured on the building roof marked by a circle in Fig. 3b. The data show that the holiday air temperature was higher than the weekday air temperature, because the holiday solar radiation was greater than the weekday solar radiation.

Figure 3b shows a map of the observation sites of the Kanda and Nihonbashi urban districts. The Kanda area

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has six observation points. The air and road-surface temperatures at these points were measured every 30 min except that road-surface temperature was measured every 1 h in the August observations. On the other hand, the Nihonbashi area has 27 observation points. The air temperatures over these points were measured every 1 hour with a portable thermometer mounted on a bicycle. The bicycle traveled the points in an order determined in advance. The observation time and temperature were simultaneously recorded. All of the measurement heights of air temperature were about 1 m above the road surface. The term "air temperature" means a temperature measured at that height, hereinafter. In the measurement, a portable thermometer was inserted into a ventilation tube that prevented the sensor from being directly heated by insolation.

Figure 5 shows the averaged structures of the study areas. These data were calculated from geographic information system (GIS) data of Tokyo, for the 120- and 200-m-radius areas (the dashed-circle areas in Fig. 3b) in Kanda and Nihonbashi, respectively. As seen in this figure, the sky-view factor of the Nihonbashi area is smaller than that of Kanda, because there are a greater number of tall buildings in the Nihonbashi area (cf. the graph of the vertical distribution of the floor density). There is not so much difference in the ratio of building or road areas to the entire area between the two areas.

b. Air and road-surface temperatures in urban districts

In Figs. 6 and 7, the air temperatures measured at the six points in Kanda and the 27 points in Nihonbashi are plotted. At both areas, the measured temperatures were mostly higher than those measured with the Automatic Meteorological Data Acquisition System (AMeDAS) of the Tokyo district meteorological observatory at the location marked in Fig. 3a. The AMeDAS measurement is carried on above the ground in an open space covered with short grass. This difference appears on both a whole weekday (Fig. 6) and holiday (Fig. 7).

Figure 8 shows the temporal variations of air temperature and their spatial distributions in the areas. In both areas, the daytime air temperatures are more scattered with location than are the nighttime temperatures. This result is shown by the standard deviation and the difference between maximum and minimum values at each time in the figure. The daytime road-surface temperatures measured at the Kanda area are also greatly scattered with location (Fig. 9); the heterogeneities of both air and road temperature distributions are significant during the daytime. This feature is attributed to the fact that the accumulated insolation received at the road surface depends on whether the place was in the sunshine or in the shade. Thus, the heterogeneity of the daytime air temperature measured near the road surface in the urban canopy layer is closely related with that of the road-surface temperature, which is controlled by the amount of sunshine at each area.

The scattering of the road-surface temperature in the Kanda area is large even in the nighttime, particularly on the holiday (Fig. 9b). However, the relative differences of air temperatures (i.e., Fig. 7a) were less than 1°C at nighttime. The daytime-averaged [1200–1800 J
Fig. 3. Site regions of the study: (a) large-scale and (b) close-up views. The dashed square in (a) is the region in Fig. 12. Roman numerals in the left panel of (b) mark the points of the temperature measurements in the Kanda area; Arabic numerals in the right panel of (b) mark the points in Nihonbashi. The thick open circle in the left panel of (b) marks the building where the radiation fluxes from the sky were measured. The larger dashed circles are the area in which parameters representing the urban district structure in Fig. 5 were calculated.
pan standard time (JST), and 0600–1200 JST] air temperature has good correlation with the road-surface temperature: the correlation coefficients are 0.82 and 0.66 for weekday and holiday, respectively. On the other hand, such a positive correlation does not appear at the nighttime (1900–0500 JST): the correlation coefficients are −0.54 and −0.25 for weekday and holiday, respectively. Therefore, the spatial distribution of the nighttime air temperature measured on the road surface in the urban canopy is most likely unrelated to that of the road-surface temperature.

4. Simulations

a. Calculation conditions

Table 1 lists the initial and boundary conditions used in the model calculations. The calculations were executed to make comparisons with the weekday and holiday observations. The upper boundary conditions of the wind and temperature equations were obtained from routine measurements at the height of 250 m on the Tokyo Tower, which is about 3 km south-southwest from the Kanda area (see Fig. 3a). During the observational periods, the longwave and shortwave fluxes of the downward radiations were measured on the building roof (about 36-m height) at the location marked with a circle in the Kanda area of Fig. 3b. These data were used for the model calculations. Table 2 shows the parameters of surface properties used in the model calculations. These parameters are the same as those of Kondo et al. (2005). Most of the road-surface material is asphalt, and that of the buildings is concrete.

The model calculations used area-averaged building parameters, including the building width, street width, and vertical floor density distribution that are shown in Fig. 5. The parameters for the BEM are shown in Table 3. These parameters, which are typical values for Tokyo office buildings, are given in Kikegawa et al. (2003). The air conditioners were assumed to be operated from 0900 to 1800 JST on weekdays. The waste heat resulting from the air-conditioning operation is emitted at the building roof as both sensible and latent heat. In the Tokyo office district, most of the waste heat is emitted from the outdoor heat exchanger on the building roof (Kikegawa et al. 2003). The ratio of sensible heat to latent heat is determined from the constituent ratio of the air-conditioning equipment; the ratio of the air-cooled equipment to the water-cooled equipment is 6:4. For the holiday calculation, the air conditioners were not operated and waste heat was not emitted into the atmosphere. This fact was confirmed by checking the electricity consumption data for the Kanda and Nihonbashi areas.

![Fig. 4. Temporal variations of air temperature (thick lines) and shortwave radiation (thin lines) at the building roof marked by the circle in Fig. 3b. The solid and dashed lines indicate the data measured on the weekday (29–30 Jul 2002) and holiday (10–11 Aug 2002) observations, respectively.](image-url)

![Fig. 5. Parameters representing the urban district structure for both areas. The average building and street widths, average sky-view factors, and vertical distributions of building floor density were evaluated from Tokyo GIS data within the dashed circle in Fig. 3b.](image-url)
The two model integrations started at 0000 JST 27 July and 8 August and ended at 1300 JST 30 July and 11 August, respectively. The calculation results on the third and fourth days were analyzed because this period was the same period as the observations. The model case runs are listed in Table 4. Case names ending with “-nc” are those that did not include waste heat from automobiles. The amounts of automobile waste heat for the weekdays and holidays were at most 100 and 40 W m\(^{-2}\) in the evening hours, respectively. These values were estimated from the number of the automobiles counted for each type at point IV in Kanda during the observation periods. The fuel consumption per unit kilometer traveled (W km\(^{-1}\)) was calculated for each type of automobile and fuel. The total consumption of the fuel (W) was derived from the multiplication of the fuel consumption by the travel length around the point IV. Then, the waste heat flux from the automobile (W m\(^{-2}\)) was obtained by dividing the total heating value by the considered area around the point. Two kinds of simulation cases were considered: BEM was calculated with indoor workers for the weekday case (hereinafter BEMwrk and BEMwrk-nc) and without indoor workers for the holiday case (hereinafter BEMnwk and BEMnwk-nc). In addition, BEMnwk-nc was also calculated for the

![Diagram](image-url)

Fig. 6. Temporal variations of the air temperature measured on 29–30 Jul 2002 (weekday observation). The marks are the measurement points (Fig. 3b) in the (a) Kanda and (b) Nihonbashi areas. The dashed lines are from AMeDAS, which are measurements over an open space covered with short grass. The location of AMeDAS is marked in Fig. 3a.
weekday case to investigate sensitivity to the waste heat.

b. Comparison between simulations and observations

Figure 10 shows that the daytime air temperature calculated with the BEMnwk-nc (crosses) is lower than the measured temperature (the averaged temperature over all the points), whereas those of the BEMwrk-nc and the BEMwrk (circles and squares) are comparable to or higher than that of the observations on weekdays. Thus, consideration of the air-conditioning operation and its waste heat by indoor activities is required to simulate a weekday air temperature accurately in an office-building area. The excess of the BEMwrk temperature is due to the overestimation of the traffic volume in Kanda, because the data were measured by the street with the biggest traffic volume in the Kanda area. On the other hand, the nighttime air temperatures calculated with the model are in good agreement with the observations. This result may be due to the disappearance of the spatial heterogeneity from the waste heat and sunshine–shade contrasts.

For the holiday case (Fig. 11), the calculated temperatures with the BEMnwk and the BEMnwk-nc are close to the measured temperatures in both the Kanda and Nihonbashi areas. In addition, the temperature rise attributable to automobiles in the holiday case is less than that in the weekday case.

We have an interest in the difference between the temperature calculated from the current model and from a mesoscale meteorological model that includes a
slab model with no urban canopy layer and that is widely used to predict meteorological fields. Here, we simulate the air temperature in the Kanda and Nihonbashi areas, using the Dry Atmospheric Regional Demonstrations (DryARD) mesoscale meteorological model, developed by Ohashi and Kida (2002a,b), for the temperature comparisons. The details of the model descriptions, land-use categories, and surface parameters (e.g., roughness length, albedo, and moisture availability) have been described in the above-mentioned papers. The calculation domain is shown in Fig. 12. We analyzed the air temperature calculated at the model grid point that includes both the Kanda and Nihonbashi areas, which is marked by “×” in the figure. The model grid interval for the horizontal direction varies with location and has a 2-km-square resolution at the analyzed point. Topography and land-use data were input as bottom boundary conditions.

The calculation with DryARD should be performed with the same parameters, initial and boundary conditions, and radiation forcing as that of the CM-BEM. However, it is too hard to make such a setting in this study. Therefore, we confirmed that the differences in the values of those factors were very small in all of the simulations.

<table>
<thead>
<tr>
<th>Table 1. Initial and boundary conditions used in the model calculations.</th>
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<tbody>
<tr>
<td><strong>Initial time of the simulations</strong></td>
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<tr>
<td></td>
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<tr>
<td><strong>Shortwave and longwave radiation fluxes</strong></td>
</tr>
<tr>
<td><strong>Initial potential temperature</strong></td>
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<tr>
<td><strong>Upper wind</strong></td>
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<tr>
<td><strong>Upper temperature</strong></td>
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<tr>
<td><strong>Height of the model top</strong></td>
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<tr>
<td><strong>Vertical resolution of the grid</strong></td>
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<tr>
<td></td>
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<tr>
<td><strong>Time step</strong></td>
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</table>
The air temperature calculated with DryARD for the holiday case is shown with the star marked in Fig. 11. The rawinsonde data at Tateno Station, which is about 50 km northeastward from these areas, were used for the synoptic winds in DryARD. This figure shows that the air temperature calculated with DryARD is lower than those from the observations and from the CM–BEM simulations during the period from noon on the first day until sunrise on the second day. This result is mainly attributed to a difference in thermal effects between a multilayer urban canopy model and a slab-type urban model and demonstrates that the effects of the buildings in the urban area should be considered more explicitly to predict the thermal environment in an urban region. Hence, our finding is consistent with that of Kusaka and Kimura (2004a,b): a nocturnal urban heat island is caused by the larger heat storage of an urban canopy (more sensible-heat release after sunset) and by the suppression of radiative cooling due to the canopy structure, through comparisons among the results of a mesoscale model with a single-layer urban canopy model and those without any urban model.

Thus, the CM–BEM model can accurately simulate holiday air temperatures in the office district by assuming no indoor activity. Kondo et al. (2005) used a mesoscale model coupled only with the CM to simulate the holiday air temperature in the same observation period. Our model reproduced the holiday air temperature more accurately than that reproduced by their model, because the observation data were used for upper boundary conditions of the model.

We now discuss the difference between the measured and calculated road-surface temperatures. The calculated road-surface temperature is a horizontally averaged value over the considered urban area, just as we did for the air temperature. As can be seen in Fig. 13, the predicted road-surface temperature agrees well with the measurements, except during the early morning on the second day, in which the predicted temperature is lower than the measured average temperature. However, the measured road-surface temperatures vary significantly with the location, especially during the daytime, as shown by the error bars (the standard deviation). Figure 13 also shows the cases of BEMwrk-nc (sun) and BEMnwk-nc (sun) in which there was no building shade (i.e., every road surface is under the

<table>
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<tr>
<th>Table 2. Surface parameters used in the CM.</th>
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<tbody>
<tr>
<td><strong>Road</strong></td>
</tr>
<tr>
<td>Albedo</td>
</tr>
<tr>
<td>Thermal conductivity (W m$^{-1}$ K$^{-1}$)</td>
</tr>
<tr>
<td>Volumetric heat capacity ($10^9$ J m$^{-3}$ K$^{-1}$)</td>
</tr>
</tbody>
</table>

| **Building** | **Wall and roof (concrete)** | **Heat insulator (polyethylene foaming board, 5 cm thick from room inside)** | **Window (30% area of exterior walls)** |
| Albedo | 0.2 | — | 0.4 |
| Thermal conductivity (W m$^{-1}$ K$^{-1}$) | 2.28 | 0.04 | — |
| Volumetric heat capacity ($10^9$ J m$^{-3}$ K$^{-1}$) | 2.01 | 0.06 | — |

<table>
<thead>
<tr>
<th>Table 3. Parameters used in the BEM.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model parameters</strong></td>
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<tr>
<td>Target temperature of room cooling ($T_{set}$)</td>
</tr>
<tr>
<td>Target relative humidity of room cooling</td>
</tr>
<tr>
<td>Duration of air-conditioning operation on weekday</td>
</tr>
<tr>
<td>Constituent ratio of air-conditioning equipment</td>
</tr>
<tr>
<td>Position of heat emission</td>
</tr>
<tr>
<td>Ratio of possible air-conditioned floor area to total floor area ($\gamma$)</td>
</tr>
<tr>
<td>Volumetric ventilation rate per unit floor area</td>
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<tr>
<td></td>
</tr>
<tr>
<td>Floor area per unit worker</td>
</tr>
<tr>
<td>Heat generation from a worker</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Sunlight transmissivity of windows ($\eta$)</td>
</tr>
<tr>
<td>Overall volumetric heat capacity of indoor air ($Q_{\text{u}}V_{\text{h}}$)</td>
</tr>
</tbody>
</table>
sunshine) and those of BEMwrk-nc (shade) and BEMnwk-nc (shade) in which there was no direct shortwave radiation on the road (i.e., every road surface is in the shade). These results indicate that the model can adequately simulate the range of the road-surface temperature between the maximum at the sunny location and the minimum at the shady location during the daytime hours. Moreover, the temperature difference among the measuring positions from daytime to nighttime, which was shown in Fig. 9, can be reproduced well in the difference between the sun and shade cases. We consequently conclude that the predicted road-surface temperature is quantitatively consistent with the measurements, similar to the results for the air temperatures.

c. Influence of air-conditioning waste heat on air temperature rise

The agreements between measured and calculated temperatures indicate that the CM–BEM can quantitatively assess the impacts of air-conditioning waste heat on the urban thermal environment. The results in Fig. 10 imply that air-conditioning waste heat causes a tem-

![Fig. 10. Temporal variations of the average air temperatures (solid line) measured in weekday observation and the air temperature (marks) predicted by three weekday-case runs in the (a) Kanda and (b) Nihonbashi areas. The error bar represents the standard deviation of the average air temperature. Squares (BEMwrk) are the simulation case with indoor worker activities and traffic, circles (BEMwrk-nc) are the case with indoor worker activities but no traffic, and crosses (BEMnwk-nc) are the case with neither indoor worker activities nor traffic.](image)

![Fig. 11. Same as Fig. 10, but for the holiday case. Squares (BEMnwk) are the simulation case with no indoor worker activities but including traffic, circles (BEMnwk-nc) are the case with neither indoor worker activities nor traffic, and stars (DryARD) show the results from the mesoscale meteorological model.](image)
perature rise of 1°–2°C on weekdays in the Tokyo office district. This value, however, is possibly underestimated, because the upper boundary temperature (i.e., the measured value at 250-m height) used for BEMnwk and BEMnwk-nc should be lower than the values that are used here, which were affected by the actual waste heat.

The CM uses many parameters associated with the physical properties and building structure, such as thermal conductivity, heat capacity, and area fraction of windows to building sidewalls. Many researchers used different values in the earlier studies (e.g., Sakakibara 1996; Martilli et al. 2002; Masson et al. 2002; Kikegawa et al. 2003). We thus investigated the sensitivity of the air temperature on the parameters used in the CM, as shown in Table 5. Here, the building surface parameters, thermal conductivity, volumetric heat capacity, and area fraction of windows were selected for the sensitivity check. The setting values were determined from the earlier studies mentioned above. The table showed that the parameter variations did not cause a decrease or increase of air temperature of more than 0.05°C.

The BEM also has the parameters of the air-conditioning operation such as the target temperature of room cooling and the constituent ratio of the heat sources. Table 6 lists the results of air temperature sensitivity on the parameters used in the BEM: target temperature of room cooling, constituent ratio of the heat sources, and ratio of potential air-conditioned floor area to total floor area. Like the above results from the CM, the sensitivity experiments showed that the parameter variations did not cause a decrease or increase of air temperature of more than 0.05°C. The other parameters little affected the air temperature in comparison with the parameters listed in Table 6. We consequently conclude that the influence of a variety of parameter values used in the earlier studies on air temperature is negligible for the influence of air-conditioning waste heat on air temperature.
5. Summary

A coupled model of multilayer urban canopy model with a building energy analysis model (CM–BEM) has been developed to investigate the diurnal variations of air temperature in an urban canopy layer of a real huge city. Observations and model simulations have been conducted for two office districts in Tokyo. The CM–BEM has accurately simulated the air temperature for a weekday case (29–30 July 2002); in this case the waste heat resulting from the energy consumption and cooling load in the buildings has significantly influenced the outdoor temperatures. On the other hand, for a holiday case (10–11 August 2002) the waste heat from the buildings has little influence on the outdoor temperatures and can be neglected in the model. The waste heat resulting from air conditioners has increased the air temperature by 1°–2°C or more on weekdays in the office district in Tokyo. This result demonstrates the importance of considering the waste heat resulting from energy consumption with air-conditioning in the calculation of urban canopy temperature. Moreover, by comparison with a mesoscale meteorological model without the urban canopy structure, it has been shown that the urban canopy structure is an important part of the model.

Thus, for air temperature predictions in big cities, it is necessary to model the interactions between the outdoor temperature and the waste heat from the air conditioners adequately. Our next study will focus on a coupling of a mesoscale meteorological model with the current CM–BEM to determine whether this more complete model can quantitatively reproduce and predict multiscale urban meteorological fields.

### Table 5. Sensitivity results of CM’s parameters. “Setting values” are the parameter values that were changed from the BEMnwk-nc. Parentheses in “Setting values” are default values (Table 2). “Temperature difference” is the average value of the temperature differences between each case and BEMnwk-nc during the period of calculations at Nihonbashi on weekday.

<table>
<thead>
<tr>
<th>CM’s parameters</th>
<th>Setting values</th>
<th>Temperature difference (each case – BEMnwk-nc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity of wall and roof</td>
<td>1.40 (2.28)</td>
<td>+0.0416°C</td>
</tr>
<tr>
<td>(W m⁻¹ K⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volumetric heat capacity of wall and roof</td>
<td>1.93 (2.01)</td>
<td>+0.0048°C</td>
</tr>
<tr>
<td>(×10³ J m⁻³ K⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area of windows</td>
<td>20 (30)</td>
<td>−0.0096°C</td>
</tr>
<tr>
<td>(%)</td>
<td>40 (30)</td>
<td>+0.0032°C</td>
</tr>
</tbody>
</table>

### Table 6. Same as Table 5, but for BEM’s parameters. Parentheses in “Setting values” are default values (Table 3).

<table>
<thead>
<tr>
<th>BEM’s parameters</th>
<th>Setting values</th>
<th>Temperature difference (each case – BEMnwk-nc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target temperature of room cooling (°C)</td>
<td>24.0 (26.0)</td>
<td>−0.0452°C</td>
</tr>
<tr>
<td>Constituent ratio of heat source</td>
<td>5.5 (6.4)</td>
<td>−0.0472°C</td>
</tr>
<tr>
<td>(air cooled.water cooled)</td>
<td>7.3 (6.4)</td>
<td>+0.0456°C</td>
</tr>
<tr>
<td>Ratio of possible air-conditioned floor area to total floor area (%)</td>
<td>50 (60)</td>
<td>−0.0188°C</td>
</tr>
</tbody>
</table>
Because the CM-BEM uses many parameters shown in Tables 2 and 3, the parameters should be specified in each grid when the CM-BEM is connected with a mesoscale meteorological model. The averaged building width, street widths, and the distribution of the building height at each grid can be obtained from GIS data. The parameters of the building structure and those of the BEM are also estimated from the use type of the building (e.g., commercial building, apartment, and wooden house) in each grid. In the usual simpler parameterization of the anthropogenic heat flux, the energy consumption of buildings and automobiles has been explicitly accumulated in the entire urban area or each model grid (e.g., Kitada et al. 1998; Kanda et al. 2001). However, the CM-BEM has the advantage that it can internally calculate the energy consumption of buildings by providing the above parameters.

Acknowledgments. We thank Dr. Hirofumi Sugawara of the National Defense Academy of Japan for his advice on the temperature measurements. This study was partially supported by a grant for Environmental Research Project from the Sumitomo Foundation of Japan and the Ministry of the Environment in Japan and Ministry of Environment of Japan.

APPENDIX

Model Descriptions

a. Urban canopy meteorological model (CM)

The vertical one-dimensional prognostic equations are given as follows:

\[ \frac{\partial u}{\partial t} = \frac{1}{m} \frac{\partial}{\partial z} \left( K_u \frac{\partial u}{\partial z} \right) - c_u a (u^2 + v^2) + f(v - u), \]

(A1)

\[ \frac{\partial v}{\partial t} = \frac{1}{m} \frac{\partial}{\partial z} \left( K_v \frac{\partial v}{\partial z} \right) - c_v a (u^2 + v^2) - f(u - v), \]

(A2)

\[ \frac{\partial \theta}{\partial t} = \frac{1}{m} \frac{\partial}{\partial z} \left( K_\theta \frac{\partial \theta}{\partial z} \right) + \frac{Q_\theta}{c_\rho \rho}, \]

(A3)

\[ \frac{\partial q}{\partial t} = \frac{1}{m} \frac{\partial}{\partial z} \left( K_q \frac{\partial q}{\partial z} \right) + \frac{Q_L}{L \rho}, \]

(A4)

where \( u, v, \theta, \) and \( q \) indicate the wind speeds of an east–west component and a south–north component, the potential temperature, and the specific humidity, respectively. The symbols \( K_u \) and \( K_\theta \) are the momentum and heat (water vapor) diffusivities, respectively, which are calculated from Gambo’s (1978) scheme. The symbols \( f, u, v, \) and \( q \) are the Coriolis parameter, the geostrophic wind speed of an east–west component, and the geostrophic wind speed of a south–north component, respectively.

Here, \( m \) is given by

\[ m = 1 - \frac{b^2}{(w + b)^2} P_w(z), \]

(A5)

where \( b \) and \( w \) indicate the building width and the road width. In additional, \( P_w(z) \) represents the floor density distribution of the buildings in the considered area at level \( z \), that is, \( 0 \leq P_w(z) \leq 1 \). Equation (A5) represents the air-volume fraction within a grid in the urban canopy. This variable significantly affects the temporal variations of meteorological elements in Eqs. (A1)–(A4). The same definitions as those of Sorbjan and Uliasz (1982) for the drag coefficient due to the building \( c \) and for the building-area density \( a \) are used.

Quantity \( Q_\theta \) in Eq. (A3) is the sensible-heat exchange between the building walls and the atmosphere, or the waste heat emitted from the automobiles and from the air conditioners. Quantity \( Q_\theta \) in Eq. (A4) is the latent-heat exchange when the wall is covered with vegetation or when the water-cooled system (cooling tower) is installed for the purpose of the heat-island countermeasure. Detailed descriptions of \( Q_\theta, Q_L, K_m, \) and \( K_h \) are in Kondo et al. (2005).

The shortwave radiation fluxes within the urban canopy layer are divided into the direct component, the scattered component from the sky, and the primary reflected component by the neighboring building. These components are geometrically calculated for the road surfaces, the roof surfaces, and the east, west, south, and north walls at each height. At the height for which \( P_w(z) \) is less than unity, the scattered and reflected radiations decrease; on the other hand, the transmitted radiation increases.

The longwave radiation fluxes within the urban canopy layer are divided into the component emitted from the sky and that from walls and roads. At the height at which \( P_w(z) \) is less than unity, in the same manner as the shortwave radiation, the longwave radiation emitted from the walls decreases.

The shading area generated by buildings is geometrically provided for the building roof, sidewalks, and the road surface. After the surface temperatures in the sunshine and shading areas are calculated separately, the area averaging of the surface temperature is severally taken for all sidewalks and the roof at each height, and road surfaces. Detailed calculation methods of radiation are in Kondo et al. (2005).
b. Building energy analysis model (BEM)

First, the thermal loads into the indoors are calculated from

\[
H_{in} = \sum_i A_i h_i (W_i - T_i) + \sum_j A_j \eta_j S_j + (1 - \beta) c_p \rho V_a (T - T_r) + A_j Q_{es} + A_f \phi_f Q_{ha} \quad \text{and} \quad (A6)
\]

\[
E_{in} = (1 - \beta) L \rho V_a (q - q_r) + A_f \phi_f Q_{hl} \quad \text{(A7)}
\]

where the subscripts \(i\) and \(j\) represent the surface elements of the indoor wall and the window, respectively. The first term on the right of Eq. (A6) is the heat conduction at the building roof and wall. The symbol \(h\) (W m\(^{-2}\) K\(^{-1}\)) represents the convective heat transfer coefficient, \(W\) (K) is the indoor wall-surface temperature, \(T\) (K) is the outdoor air temperature, and \(T_r\) (K) is the indoor air temperature. The second term is the insolation through the window. The symbol \(\eta\) (unitless) represents the sunlight transmissivity of the window, and \(S\) (W m\(^{-2}\)) is the solar irradiance through the window. The third term is the sensible-heat load by ventilation. The symbol \(\beta\) (unitless) is the thermal efficiency of the total heat exchanger, and \(V_a\) (m\(^3\) s\(^{-1}\)) is the volume of the outdoor air inflow. The fourth and the last terms are the sensible-heat generations from equipments and workers in the building, respectively. Here, \(A_j\) (m\(^2\)) is the floor area of the building, \(Q_{es}\) (W m\(^{-2}\)) is the amount of sensible-heat generation from equipment, \(P\) (persons per square meter) is the maximum number of hourly working persons to \(P\), and \(Q_{ha}\) (watts per person) is the amount of sensible-heat generation from workers.

On the other hand, Eq. (A7) is the latent-heat component of the thermal loads into the indoors, which consists of the latent-heat loads by ventilation (the first term) and the indoor latent-heat generation from the workers (the second term). The symbol \(L\) (J kg\(^{-1}\)) is the latent heat of evaporation, \(\rho\) (kg m\(^{-3}\)) is the air density, \(q_r\) (kg kg\(^{-1}\)) is the indoor specific humidity, and \(Q_{hl}\) (watts per person) is the amount of latent-heat generation from workers.

To determine \(W_a\), a heat balance equation on the indoor wall surface is solved in conjunction with the one-dimensional thermal conduction equation in the wall, for each element of the indoor surfaces. At the same time, the heat budget on the outdoor wall surface is also calculated in the CM.

The remaining unknown variables, \(T\), and \(q_r\), are calculated from the use of

\[
Q_B \frac{dT_r}{dt} = H_{in} - H_{out} \quad \text{and} \quad (A8)
\]

\[
L \rho V_B \frac{dq_r}{dt} = E_{in} - E_{out}, \quad \text{(A9)}
\]

where \(Q_B\) (J K\(^{-1}\)) and \(V_B\) (m\(^3\)) denote the overall heat capacity and the total volume of the indoor air in the building, respectively; \(Q_B\) includes the heat capacity of interior structures such as furniture and inner walls. Respectively, \(H_{out}\) (W) and \(E_{out}\) (W) are the sensible and latent heat pumped out from the building for cooling. The calculation of these values is modified from Kikegawa et al. (2003) as follows:

\[
H_{out} = \xi \gamma \left( H_{in} + Q_B \frac{T_r - T_{set}}{\Delta T} \right) \quad \text{and} \quad (A10)
\]

\[
E_{out} = \xi \gamma \left( E_{in} + L \rho V_B \frac{q_r - q_{set}}{\Delta T} \right). \quad \text{(A11)}
\]

Here, \(\xi\) (0 \(\leq\) \(\xi\) \(\leq\) 1) is the ratio of actual air-conditioned floor area at some hour to the maximum possible air-conditioned floor area, and \(\gamma\) is the ratio of possible air-conditioned floor area to the overall floor area within a building. The symbols \(T_{set}\) (K) and \(q_{set}\) (kg kg\(^{-1}\)) are the target temperature and specific humidity of the outdoor heat exchanger by air conditioner, respectively; \(\Delta T\) is the time step for the model integration.

As can be seen in Eqs. (A8) and (A9), the indoor temperature \(T_r\) and humidity \(q_r\) are determined from the difference between the heat loads provided into the building room and those removed out of the building room by air-conditioning operations. Both \(T_r\) and \(q_r\) are assumed to be uniform throughout all of the air-conditioned space of the building.

The waste heat from the outdoor heat exchanger consists of the sum of the energy (electricity and town gas) consumed by the air conditioners and the interior heat removed by the air-conditioning operation:

\[
Q_{anth} = EC + (H_{out} + E_{out}). \quad \text{(A12)}
\]

The air-conditioning energy consumption EC that is required to estimate \(Q_{anth}\) is

\[
EC = (H_{out} + E_{out})/COP, \quad \text{(A13)}
\]

where COP is the coefficient of performance of the heat pump system. The COP represents the overall energy efficiency of the air conditioner, and its magnitude depends on each type of air-conditioning system. The magnitude of the COP also depends on the air temperature around the outdoor heat exchanger; thus, COP is a function of the air temperature at the height of the exchanger. The operating power for auxiliary machinery such as the cooling-tower pump and supply
fan was excluded from the computations. We calculated the sensible-heat and latent-heat components separately and distinguished between air-cooled and water-cooled systems. Then, the emitted waste heat $Q_{\text{anth}}$ is added in the temperature and humidity prognostic equations, respectively, of the CM.

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