Numerical Simulation of the Surface Air Temperature Change Caused by Increases of Urban Area, Anthropogenic Heat, and Building Aspect Ratio in the Kanto-Koshin Area

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Abstract

We investigated a warming trend in the Kanto-Koshin area during a 30-year period (1976–2006). The warming trends at AMeDAS stations were estimated to average a little less than 1.3°C/30 years in both summer and winter. These warming trends were considered to include the trends of large-scale and local-scale warming effects. Because a regional climate model with 20-km resolution without any urban parameterization could not well express the observed warming trends and their daily variations, we investigated whether a mesoscale atmospheric model with an urban canopy scheme could express them.

To make the simulations realistic, we used 3 sets of real data: National Land Numerical Information datasets for the estimation of the land use area fractions, anthropogenic heat datasets varying in space and time, and GIS datasets of building shapes in the Tokyo Metropolis for the setting of building aspect ratios. The time integrations over 2 months were executed for both summer and winter. A certain level of correlation was found between the simulated temperature rises and the observed warming trends at the AMeDAS stations. The daily variation of the temperature rises in urban grids was higher at night than in the daytime, and its range was larger in winter than in summer. Such tendencies were consistent with the observational results.

From factor analyses, we figured out the classic and some unexpected features of urban warming, as follows: (1) Land use distribution change (mainly caused by the decrease of vegetation cover) had the largest daytime warming effect, and the effect was larger in summer than in winter; (2) anthropogenic heat had a warming effect with 2 small peaks owing to the daily variation of the released heat and the timing of stable atmospheric layer formation; and (3) increased building height was the largest factor contributing to the temperature rises, with a single peak in early morning.

1. Introduction

Surface air temperature warming trends derived from long-term observations in Japan are well known. The trends reflect the global warming baseline shift, but the magnitude of the shift, especially

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in urban areas, is obviously larger than expected. The excess magnitude is attributed to the so-called urbanization effect, that is, an effect of human activities. Recently, Fujibe (2009) estimated urban warming trends over 27 years (from 1979 to 2006) by using observational data from the Automated Meteorological Data Acquisition System (AMeDAS). The study showed that annual mean temperature warming trends ranged from approximately 0.3°C per decade (at AMeDAS observatories surrounded by the smallest population densities) to 0.5°C per decade (at observatories with the largest densities). This analysis suggests an association between urban temperature trends and human activities.

As shown by Fujibe (2010) in a review of urban warming in Japanese cities, the warming effects of urban surfaces are more apparent at night, in particular during the cold season, corresponding to a low mixing depth in the stable surface layer. During the past few decades, however, studies of urban climatology in Japan have taken a strong interest in the midsummer heat load of cities because of its association with an increased risk of heat stroke. He also observed that the region having the greatest temperature increase (more than 1°C per 30 years) in the summer extended from the vicinity of Tokyo to the northwestern corner of the Kanto Plain. This result is consistent with the findings of a decrease in daytime pressure at the center of the Kanto Plain and a shift of wind direction toward the area of lower pressure (Fujibe 1994, 2003).

Besides observational research, simulation studies of urban climatology have been performed. Using their local climate model, Kimura and Takahashi (1991) assessed the effects of anthropogenic heat load and land use modification from vegetation to urban surfaces on the surface air temperature in the Kanto Plain. Their simulation was performed under atmospheric conditions averaging 36 typical clear summer days. The temperature rise induced by the addition of anthropogenic heat and the modification of land use was estimated to be approximately 3°C (nighttime) and 1°C (daytime) at the center of the Tokyo Metropolitan area. They concluded that the anthropogenic heat load is the main cause of nighttime warming and diminished vegetation is the primary cause of the temperature rise during the daytime. Ichinose et al. (1999) also conducted a numerical simulation with a more detailed and realistic distribution of the anthropogenic heat. Their simulation showed that the sur-

face air temperature could rise by about 1.5°C on a summer day and by about 2.5°C on a winter day, peaking at late evening at the center grid of the heat distribution.

Kusaka et al. (2000) provided 3 different bottom boundary conditions for their mesoscale model by using land use information from 1900, 1950, and 1985. After performing some sensitivity experiments using the 3 land use scenarios under typical summer atmospheric conditions, they estimated that the warming bias might be about $2\text{--}3^{\circ}\text{C}$ over 85 years (1990–1950) and about $1\text{--}2^{\circ}\text{C}$ over the later 35 years (1950–1985). They also noted that the warm bias areas were distributed around the outer part but not in the center of the Tokyo Metropolitan area.

Kusaka and Kimura (2004a, b) estimated urban canyon effects, such as redistribution of radiation, heat transfers among surfaces in the canyon, and reduction of wind speeds inside the canopy layer, using their 2-dimensional atmospheric model to which they coupled their urban canopy model (Kusaka et al. 2001). The results of their simulation showed that urban warming could occur by only the canyon effects of urban buildings.

These earlier numerical studies on urban warming succeeded as a sort of factor analysis. Their simulations, however, were carried out under idealized or other clear and calm atmospheric conditions. Therefore, a simple comparison cannot be made between such warming bias predictions and observational temperature trends of the real atmosphere, in which many atmospheric phenomena can occur. The surface changes must be sensitive to the weather conditions. Furthermore, there are possible interactions between urban surfaces and meteorological phenomena, such as cloud generation caused by the urban heat load (Inoue and Kimura 2004, 2007).

To estimate the sensitivity of land surface modification to urban warming effects more accurately, reproduction experiments with increased realism have recently been employed that use mesoscale models incorporating the concept of urban canopy energy balances coupled to their land surface schemes. Numerical simulations using cloud resolving non-hydrostatic models are mainly performed with realistic initial and boundary conditions based on reanalysis data. Kusaka et al. (2009) tried to reproduce the summer meteorological fields of 2002, 2003, and 2004 by targeting the Weather Research and Forecast model (WRF) onto the Kanto area,

and they showed the availability of the WRF model to climatic research. Adachi and Kimura (2010) researched the urban effects of 10 years of land use modification (from 1987 to 1997) on the nighttime temperatures of cities in the Kanto Plain by conducting simulation with their Terrestrial Environment Research Center version of the Regional Atmospheric Modeling System (TERC-RAMS). They conducted the TERC-RAMS simulations with experimental matrices under the following conditions: 2 surface boundary conditions of 1987 and 1997, 2 atmospheric boundary conditions of the 1980's and 1990's downscaled from Japanese re-analysis (JRA-25) datasets (Onogi et al. 2007), and atmospheric conditions derived by the pseudo-global warming downscaling method (Kawase et al. 2009). They pointed out that urban warming during the nighttime (0200–0400 LST) in August from 1987 to 1997 might be about 0.3–0.4°C around the center of the Tokyo Metropolitan area. Hara et al. (2010) checked the sensitivity of the atmospheric stability, which will change after global warming, to the urban heat island intensity in winter by a numerical simulation with the WRF model. They showed that the nighttime urban heat island will grow on average in winter as the atmosphere becomes more stratified by future global warming. Although their interest was in the relationship between global warming and the urban heat island, their research showed that the WRF system can be

applied to urban climate research on wintertime effects.

Likewise, our intention was to reproduce the urban warming potential caused by urban growth in recent decades by numerical simulations with our non-hydrostatic atmospheric model. In this paper, we compare the results with observed temperature trends. For a more consistent comparison, we use land use information from the years corresponding to the observational dataset. After evaluating the reproducibility and checking the limitation of the reproduction, we perform some classic sensitivity studies of urban effects, that is, the effects of decreased vegetation area, anthropogenic heat load, and the structural change of urban building canopies.

2. Warming trends in the Kanto-Koshin area

The study area was the Kanto-Koshin region in eastern central Japan. First, we briefly review warming trends from 1976 to 2006 observed at the AMeDAS stations. Figure 1 shows the distributions of seasonally averaged temperature trends for summer (July and August) and winter (January and February) as derived by a simple regression method. Only data without any statistical disconnection during the years of the study period were used. A bigger square represents a warmer trend at the station and a variety of symbols show the t-test significance levels. Table 1 lists the trends

Fig. 1. Daily average temperature trends and their significances at AMeDAS stations. The size of the square represents the trend. The indicated marks represent the significance levels of the trends.

Table 1. AMeDAS stations in the study area (the Kanto-Koshin region). The trends and their significances derived from 31 years (1976–2006) of observational data are also listed.

Station ID	Station Name	Trend [$^{\circ}\text{C}/30$ years]		Significance [%]	
		summer	winter	summer	winter
36476	KOORIYAMA	1.69	1.52	95	98
36667	SHIRAKAWA	1.16	1.31	87	95
40201	MITO	1.28	1.30	89	96
41141	OTAWARA	1.12	1.33	88	96
41166	OKUNIKKO	1.26	1.01	96	82
41277	UTSUNOMIYA	1.64	2.05	96	99
42251	MAEBASHI	1.67	1.36	95	96
42266	KIRYU	0.92	1.14	76	93
43056	KUMAGAYA	1.86	1.67	97	99
43156	CHICHIBU	1.43	1.55	94	98
44131	TOKYO	1.53	1.48	94	98
45147	CHOSHI	0.81	0.97	77	85
45212	CHIBA	1.74	1.75	97	99
45371	KATSUURA	0.71	1.22	79	94
45401	TATEYAMA	1.05	0.82	92	84
46106	YOKOHAMA	1.43	1.44	95	98
48156	NAGANO	1.06	1.14	89	87
48256	UEDA	0.50	0.62	54	61
48331	KARUIZAWA	1.59	1.37	98	92
48361	MATSUMOTO	1.46	0.94	97	78
48491	SUWA	1.55	1.33	99	87
48606	KISO-FUKUSHIMA	1.59	1.09	99	82
48767	IIDA	1.65	0.92	99	80
49142	KOFU	1.72	1.65	99	99
49251	KAWAGUCHIKO	1.67	1.37	99	94
50206	MISHIMA	1.49	1.40	98	97
50281	AJIRO	1.06	1.02	88	91
50331	SHIZUOKA	1.03	1.16	91	94
50456	HAMAMATSU	1.28	1.31	96	94
50551	OMAEZAKI	0.67	1.45	74	96
50561	IROZAKI	0.68	0.90	75	86
54651	TAKADA	1.09	1.25	89	94

and significance levels at each station. Simple averaged warming trends were estimated to be a little less than $1.3^{\circ}\text{C}/30$ years for both summer and winter. Note that all of the trends were positive in both seasons. Among the trends with a significance level of over 80%, 8 stations (station IDs 42251, 48331, 48491, 48606, 48767, 49251, 44131, and 45401) had larger trends in summer than in winter and only 2 stations (41277 and 43156) had warming trends larger in winter than in summer. It can be seen that the inland warming trends were larger than the coastal ones in both seasons.

Figure 2 shows the seasonal daily trends at the individual stations. The seasonal averages over 2 months of the 24-hourly surface air temperatures were determined and their yearly trends were estimated. Stations were classified into 3 types: A) stations with large warming trends during the daytime, B) stations with flat trends throughout the day, and C) stations with small warming trends during the daytime. The classification was performed as follows. First, stations with a standard deviation within 0.1°C for each of 24 hourly values were categorized as group B. Next, the stations whose averaged trends during daytime (0600–1800 LST for summer, 0700–1700 LST for winter) were larger than during the night were categorized as group A. Other stations were categorized to group C. Following this procedure, for summer, 27 stations were sorted equally into groups A, B, and C. For winter, however, almost all of the stations were categorized as group C. Figure 2D shows the time series of differentials between the 1990's and 1980's climatic surface air temperatures around the Kanto-Koshin area as simulated by the Non-Hydrostatic Regional Climate Model (NHRCM; Ishizaki et al. 2009), downscaled from JRA-25 without any consideration of urban effects. Compared to the observational results, the warming trends of the NHRCM are considerably underestimated in summer and slightly overestimated in winter. Furthermore, the daily variations of the warming trends are very poorly reproduced. Such discrepancies are probably caused by the lack of urban effects in the NHRCM.

Next, by utilizing a meteorological mesoscale model, we investigate whether urbanization effects, such as the decrease of vegetation, increase of anthropogenic heat, and structural changes inside urban areas, can explain the average or the daily variation of these warming trends.

3. Experimental setting

The aim of this study was to check the reproducibility of the daily variations of observational warming trends during a 30-year period, as described in the previous section, using a sophisticated atmospheric model. In particular, we estimate the contributions of land surface modifications to the warming by altering the bottom boundary conditions of the atmospheric model. A brief introduction to the atmospheric model and urban parameterization scheme coupled to the model is presented in this section. The specifications of the initial and boundary conditions, the settings, and the data used in the reproduction and some sensitivity experiments are also described.

3.1 Atmospheric model

The base model used in this study is the Japan Meteorological Agency Non-Hydrostatic Model (JMA-NHM; Saito et al. 2007). The JMA-NHM is a fully compressible atmospheric model that was adopted as an operational regional mesoscale model at the JMA. The main specifications are described in Table 2. We selected the operational settings for almost all of the settings for the model.

For urban grids, however, we adopted the single-layered urban canopy scheme of Aoyagi and Seino (2011) instead of the default simple slab type surface scheme. This urban canopy scheme is an extended version of the energy balance scheme of urban canopy models originally proposed by Masson (2000) and Kusaka et al. (2001). The 3-dimensional consideration of the estimation of radiation distributions by building canopies and the consideration of latent heat fluxes from stored water on the building surfaces are parts of our urban scheme in this study, which we extended from the original models. Figure 3 are schematic images of a flux circuit of this urban canopy scheme and an ordinary slab scheme. The application of the urban canopy scheme enables us to describe urban radiative effects and the modifications of heat fluxes from the canopy surfaces.

Using this atmospheric model, we executed several simulations of the Kanto-Koshin area with a horizontal grid scale of 4 km. Operational mesoscale analysis (MANAL) data of the JMA were used as the initial atmospheric conditions. For summer simulation, MANAL data of 25 June 2006 0000 UTC were used as the initial conditions. Continuous integration over about 2 months was

Fig. 2. Daily seasonal variation of temperature trends. (A) Groups of observatories having trends with an upward convex shape, (B) with flat daily variation, and (C) with a downward convex shape. (D) Daily variation of the temperature trends derived from the 20 years dataset (1981–2000) of the NHRCM-20km simulation results, downscaled from JRA-25.

executed while providing the 3 hourly MANAL data as lateral boundary conditions of the simulation. After about 1 week spin-up, the half hourly output from 01 July 2006 0000 UTC to 31 August 2006 2330 UTC was used for the analysis. For

winter simulation, MANAL data from 25 December 2006 0000 UTC were used as the initial conditions and simulated data from 01 January 2007 0000 UTC to 28 February 2007 2330 UTC were used for the analysis.

Table 2. Principal specifications of the JMA-NHM.

Governing equations	Fully compressible non-hydrostatic equations
Horizontal discretization	Grid point method
Treatment of advection term	Fourth-order flux form, advection corrected
Map projection	Lambert conformal projection
Vertical grid series	Hybrid z^* -coordinate, Ishida (2008)
Topography	GTOPO30
Sea-Land distributions	National Land Numerical Information
Cloud microphysics	Bulk scheme with ice phase predict qv , qc , qr , qi , qs , qg
Cumulus parameterization	Kain-Fritsch & Cloud microphysics
Turbulent closure	Improved Mellor-Yamada Level 3
Cloud radiation	Kitagawa (2000)
Clear sky radiation	Yabu et al. (2005)
Clouds in radiation processes	Partial condensation scheme; Hara (2008)
Solid water content	Force restore method
Surface parameters	Proportional distribution by land use area
Surface scheme	Beljaars and Holtlag (1991) +Urban canopy scheme (urban grids only)

Fig. 3. Schematic images of the flux circuits. The left image represents the urban canopy scheme used for the urban grids. The right image represents the slab surface scheme used otherwise for the non-urban grids.

3.2 Land use settings

The land surface parameters used as the bottom boundary conditions were derived from the 1976 and 2006 versions of the National Land Numerical Information (land use data) provided by the Ministry of Land, Infrastructure, Transport and Tourism of Japan. The area fractions of 11 types of surface

categories are stored in the land use dataset with a grid spacing of about 100 m. A stacked bar chart of occupancies and a bar chart of the increase or decrease of each category from 1976 to 2006 in the study area are shown in Fig. 4. It is obvious that the building lot area increased significantly and vegetation areas of paddy field, farm area, and

Fig. 4. The area fraction differences between the 1976 and 2006 land use datasets (top). The increase or decrease of each land use type in the form of cell ($\sim 100 \text{ m} \times 100 \text{ m}$) counts stored in the original National Land Numerical Information datasets (middle). The horizontal distribution of the increases and decreases of the urban area fraction in $4 \text{ km} \times 4 \text{ km}$ grids, which were used in the numerical simulations executed in this study (bottom).

forests decreased. Note that the golf area was re-categorized in the newer version of the land use data and thus divided from the forest area. We assumed that the 3 categories of building lots, road,

and unclassified area were urban surfaces. The bottom image in Fig. 4 shows the horizontal distribution of urban surface fraction differences between 1976 and 2006. Over almost all of the study area, the urban area increased. The increased area of urban surface is clearly seen in the northern part of the Kanto Plain, in the area surrounding Tokyo's 23 wards, along parts of the coastline, and along some of the trunk railway lines and highways. It is noteworthy that the area fraction of urban surfaces did not change around central Tokyo. This implies that by 1976 the urban surfaces had already been saturated in central Tokyo.

The 4-km grids that are covered with over 50% of urban surface are referred to as “urban grids” in this study. We applied the urban canopy scheme to the urban grids in order to consider the effects of buildings on radiation distribution and heat transfer. Buildings were assumed to occupy 60% of the building lots and to be regularly arranged in an urban grid with an average height of 10 m. The residual 40% of building lots and the other types of surfaces were assumed to be ground area in urban canyons. The parameters of the ground area were set by a weighted average by area of the parameters listed in Table 3, such as wetness, albedo, volumetric heat capacity, and thermal conductivity. Table 4 shows the parameters of the office buildings considered in the urban canopy scheme. We applied the slab surface scheme for the other non-urban grids. The parameters for the slab scheme were also set by the area-weighted average values of Table 3.

3.3 Anthropogenic heat load

The heat load due to human activity has one of the largest impacts on the surface air temperature. We used the realistic anthropogenic heat distributions with daily variations proposed by Senoo et al. (2004). This anthropogenic heat model does not consider any heat pump effects as more sophisticated building energy analysis models (Kikegawa et al. 2003; Ohashi et al. 2007) used to estimate the heat released from buildings do. However, the heat transmitted into the building from the exterior environment through roofs and walls was released efficiently in the form of heat fluxes from the surfaces owing to insulation layers and air spaces, as listed in Table 4. Although the original dataset was provided with a grid resolution of $10''$ in latitude and longitude (about $250 \text{ m} \times 300 \text{ m}$), the values were averaged with a resolution of 4 km for this study. Anthropogenic heat was loaded only onto the

Table 3. Parameter list for each land use type used in the land surface schemes of the JMA-NHM.

Type	Wetness*	Albedo	Volumetric heat capacity [J K ⁻¹ m ⁻³]	Thermal conductivity [m ² s ⁻¹]	Roughness* [m]
paddy	0.8/0.3	0.18	1.7×10^6	0.7×10^{-6}	0.3/0.2
farm	0.4/0.3	0.20	1.7×10^6	0.5×10^{-6}	0.3/0.2
forest	0.35/0.3	0.20	1.7×10^6	0.5×10^{-6}	3.0/3.0
wasted	0.1/0.1	0.25	1.6×10^6	1.4×10^{-6}	0.1/0.1
building	0.02/0.02	0.20	2.0×10^6	1.5×10^{-6}	3.0/3.0
road	0.03/0.03	0.25	2.0×10^6	2.0×10^{-6}	1.0/1.0
other	0.1/0.1	0.25	2.0×10^6	1.0×10^{-6}	0.5/0.5
river, lake	0.65/0.65	0.10	4.2×10^6	0.8×10^{-6}	0.05/0.05
coast	0.5/0.5	0.15	2.9×10^6	0.74×10^{-6}	0.1/0.1
sea	1.0/1.0	0.10	1.9×10^6	1.3×10^{-6}	0.001/0.001
golf	0.35/0.25	0.15	1.8×10^6	0.5×10^{-6}	0.4/0.1

* (summer/winter)

Table 4. Parameters for the office building materials used in the urban canopy scheme as quoted from ECCJ (2005).

	Material	Thickness [m]	Volumetric heat capacity [J m ⁻³ K ⁻¹]	Thermal conductivity [W m ⁻¹ K ⁻¹]
Roof	Lightweight concrete	0.06	1.607×10^6	0.779
	Polystyrene board	0.025	3.516×10^4	0.037
	Asphalt	0.01	9.209×10^5	0.11
	Ordinary concrete	0.15	1.934×10^6	1.395
	Air space	0.01	1.19×10^3 * ¹	0.0241* ²
	Plasterboard	0.009	1.633×10^6	0.791
	Asbestos acoustic board	0.012	2.512×10^5	0.064
Wall	Tile	0.008	2.009×10^6	1.279
	Mortar	0.02	1.591×10^6	1.512
	Ordinary concrete	0.15	1.934×10^6	1.395
	Air space	0.01	1.19×10^3	0.0241
	Plasterboard	0.012	1.633×10^6	0.791

*¹ estimated from the density and constant pressure specific heat of air at 25°C.*² value for air at 0°C.

urban grids in the simulation for 2006. Because the anthropogenic heat dataset had been prepared only for the Tokyo Metropolis and 6 prefectures around Tokyo, the anthropogenic heat was set to 0 for

any urban grids in other prefectures. Figure 5 shows the horizontal distributions of the average anthropogenic heat in summer and winter. The heat was loaded in the form of sensible and latent

Fig. 5. Horizontal distributions of the seasonal averaged anthropogenic heat in the form of sensible heat (top) and latent heat (middle). As an example, the bottom plots represent the time variations of anthropogenic heat added to the Tokyo grid.

heat fluxes. It can be seen that anthropogenic heat is concentrated around central Tokyo. The amount of heat in that area is 10 W m^{-2} larger in winter than in summer. The unique daily variation was considered at each urban grid. As an example, the bottom plots of Fig. 5 show time series of the anthropogenic heat at the Tokyo grid.

3.4 The building aspect ratio

Modifications of the aspect ratio of urban buildings during the 30-year period were also considered. The urban canopy scheme used in this study assumed that all buildings were square prisms in shape. Thus, the only parameter specifying the building shape was the ratio of height to width (H/B). In the experiments for 2006, the H/B ratios were set from the GIS dataset of the Tokyo Metropolitan assessed on 2001 and 2002. The datasets consist of several million polygons, each representing a building in the Tokyo Metropolitan. Figure 6 shows the horizontal distribution of 100 m grid averaged H/B datasets. It can be seen that the H/B values are larger (about 1–3) at the center of the urban area and smaller in the suburban area and in the western rural areas of Tokyo. We averaged these data into 4 km grids. We applied a value of $H/B = 0.75$ (the modal class of the histogram at

0.25 intervals) to the urban grids of the other prefectures, where there was no information on the building aspect ratios. For the simulation of 1976, the Tokyo Metropolitan government (1977) reported that the achievement rate of the plot ratio averaged about one third (33.7%) for the private sector in 1975. Under the assumption that the legal plot ratio remained the same during the 30 years and that buildings have grown high enough to achieve the legal plot ratio, we supposed that the buildings were one third lower in 1976 than in the late 2000's. Thus we took the value of $H/B = 0.25$ for all the buildings in the simulations of 1976.

3.5 Experimental cases

Using the above-mentioned atmospheric model and settings datasets, we performed numerical simulations for various cases. Table 5 lists the bottom boundary settings for the experimental cases in this study. Note that only EXP2006HR, which used atmospheric data of 2006 (and 2007 for the winter case), the land use distribution of 2006, anthropogenic heat datasets of the 2000's, and building shape distribution data of the 2000's, can be called a "reproductive experiment". The other experiments were sensitivity studies for checking the effects of the bottom boundary conditions.

Fig. 6. Distribution of building aspect ratios in the Tokyo Metropolitan derived from the GIS dataset compiled by the Tokyo Metropolitan government.

Table 5. List of the experiments performed for this study. The last 3 experiments were sensitivity studies.

EXP. NAME	Land use information	Anthropogenic heat release	Building aspect ratio Height : Width
EXP1976	1976	Not Considered	1 : 4
EXP2006HR	2006	Considered	3 : 4 ^{*1}
EXP2006	2006	Not Considered	1 : 4
EXP2006H	2006	Considered	1 : 4
EXP2006R	2006	Not Considered	3 : 4 ^{*1}

^{*1} Aspect ratios in the Tokyo Metropolis were determined from the GIS dataset.

4. Results

4.1 Overall effects

The upper panels of Fig. 7 show the differentials of the surface air temperature averaged over 2 months between experiments EXP2006HR and EXP1976. Warming biases over almost the entire Kanto-Koshin area can be seen in association with the effects of land use change, anthropogenic heat load, and the increased building height. The positive bias was smaller along the coast and larger around the Tokyo Metropolitan area and in the inland urban area. Although the situations were similar in both summer and winter, the biases were larger in winter than in summer.

To determine the reproducibility of the real temperature trends over the 30-year period (Fig. 1), we examined the bottom plots in Fig. 7, which show scatter diagrams between the observational trends and the differentials (EXP2006HR-EXP1976) at the grid point where the corresponding station lies. A rough one-to-one relationship can be seen between them, although some points (Tokyo and Takada) deviate by quite a lot from the rest of the population. The correlation coefficients were 0.294 with a significance level of 90% for the summer case and 0.444 with a significance level of 99% for the winter case. The y-intercept around 1.0°C/30 years can be recognized as the trend without urbanization effects, that is, the global warming trend. This estimated value is consistent with the temperature trend of approximately 0.3°C per decade in the Northern Hemisphere for 1979–2005 reported by the IPCC (2007).

Figure 8 shows the daily variation of temperature differences between EXP2006HR and EXP1976. Spatial averaging among all of the urban grids was performed in both experiments. A smaller temperature rise in the daytime and a larger one during

the night, which is the same tendency as that of the observational trends (Fig. 2C), can be seen. The magnitude relation of the diurnal range (i.e., the winter case is larger than the summer case) and the magnitude itself are well reproduced if Fig. 2C is considered to be typical of daily variations affected by urbanization.

4.2 Factor analyses

As mentioned in section 3.2, we performed additional experiments to identify how each factor affects the warming trends. The differentials of 2 months' average temperatures are shown in Fig. 9. The differentials are A) EXP2006-EXP1976, B) EXP2006H-EXP2006, and C) EXP2006HR-EXP2006H, which represent the warming effects by the decrease of vegetation, the addition of anthropogenic heat, and the growth of building heights, respectively. Figure 10 shows the daily variation of the differentials averaged over all the urban grids for 2006.

The warming effect due to land use change, that is, area fraction changes, was larger in the area surrounding central Tokyo. The effect was also larger in inland urban areas. These areas experienced similar land use changes, namely, large decreases in the vegetation fractions, replaced by urban surfaces. Thus, the warming effect in the daytime can be explained by the well-known Bowen ratio effect. Along with vegetation decrease (the growth of urbanization), the latent heat fluxes from the surfaces become smaller and instead the sensible heat fluxes become larger. The larger sensible heat flux warms up the surface air. From the daily variation of the land use change effect (the lines with closed circles in Fig. 10), the variation seems to coincide with the movement of the sun during the day. This synchronous variation with the movement of the sun supports the idea that the temperature rise was

Fig. 7. Differentials of the averaged surface air temperature between the simulations of EXP2006HR and EXP1976. The bottom scatter plots show the correlations between the observed trends and the temperature differentials at the corresponding grids of the AMeDAS stations.

caused by the Bowen ratio effect. The result shows the point where the Bowen ratio effect was larger in the moist summer than in the dry winter. The figure also shows slight warming differentials during the night. Increased urban area in place of vegetation intrinsically led to more buildings, which resulted in the slight nighttime warming by inhibition of radiative cooling.

Figure 9B shows the horizontal distribution of the differentials of EXP2006H-EXP2006, representing the anthropogenic heat effect on the warming trend. Not surprisingly, the warming area was limited to around the area where anthropogenic heat was released. The warming rate in winter

was around 2°C, and was larger than in summer (around 1°C). Figure 11 shows a scatter plot with regression lines between the loaded heat amounts versus temperature increases at the urban grids. The heating efficiency was obviously larger in winter. There are 2 possible causes: the amount of anthropogenic heat was originally larger in winter, or the effect of heat release tended to be stronger in winter when the average height of the atmospheric boundary layer is lower and when a stable stratified surface layer is often formed. Some overheated grids where the rate of temperature rise was much larger than the regression lines can be seen in Fig. 11. The closed circles represent grids at which

Fig. 8. Daily variations of the temperature differential between EXP2006HR and EXP1976 for summer and winter. Dotted lines, thin lines, and thick lines describe the results averaged over urban grids, rural grids, and all over the land grids, respectively.

the temperature rose more than 1.5 times more than the regression lines. At these grids, there were probably other atmospheric causes of the overheating.

Figure 9C shows the effect of the growth of building heights within the urban area. The effect was larger for grids with a larger urban area fraction, and was larger in winter than in summer. An increase of the building aspect ratio causes the surface temperature to decrease in the daytime by redistributing downward shortwave radiation to the increased surface area. Conversely, it also causes the surface temperature to increase at night by inhibiting radiative cooling in the lower layers of the building canopies. These effects behave as if the effective thermal inertia of the whole surface system becomes larger. Figure 12 shows the daily variation of the radiative surface temperature differentials between EXP2006HR and EXP2006H for the Tokyo grid. For this grid, the aspect ratio H/B was assumed to change from 0.25 to 0.88. The surface temperature decreased in the daytime and increased at night as affected by the aspect ratio change. By considering the daily average, the surface temperature change was positive because the warming effect by inhibition of radiative cooling during the night was larger than the cooling effect by redistribution of downward shortwave radiation during the day. The longer nights in winter seemed to increase the surface temperature.

4.3 Nonlinear responses of the atmosphere

Since the atmosphere is a nonlinear system, quantitative comparisons of these warming effects

should be made carefully. Figure 13 shows scatter plots between the differentials (EXP2006HR-EXP2006H) and (EXP2006R-EXP2006) of all the land grids. These 2 differentials should represent the warming effects of the building aspect ratio changes. The closed circles represent the grids for which anthropogenic heat was added in the heat load experiments (represented by HR and H), and the open circles represent the grids with no heat load in any experiment. Naturally, the points of the no heat load grids are aligned almost along the one-to-one relation line. On the other hand, the temperature rise related to the aspect ratio change was smaller at the grids with anthropogenic heat. This can be explained by the larger vertical mixing processes. If anthropogenic heat is released into the lower part of the atmosphere, the atmosphere will be in a more unstable stratification condition and the vertical mixing will be slightly larger. Under such a situation, additional heat fluxes caused by other factors, such as the aspect ratio changes, probably tend to easily transfer to the upper atmosphere. With this understanding, we call the warming effects of modifications to the bottom boundary conditions on the surface air temperature derived at the previous section a kind of “warming potential.”

5. Discussion

We examined warming tendencies caused by land use modifications over a recent 30-year period. Larger warming differentials were seen for inland

Fig. 9. Differentials of the averaged surface air temperature between the experiments of (A) EXP2006 and EXP1976, representing the effects of the land use area fraction changes; (B) EXP2006H and EXP2006, representing the effects of the anthropogenic heat releases; and (C) EXP2006HR and EXP2006H, representing the effects of the building aspect ratio changes.

Fig. 10. Time variations of the temperature differences averaged between the experiments. The differentials were averaged over all urban grids.

Fig. 11. Scatter diagrams between the anthropogenic heat amounts added to the urban grids and the temperature increases at the grids. The closed circles indicate grids whose temperatures rose more than 150% more than the regression lines.

grids having large land use changes and strong urban growth, with less warming along the coast-lines. These warming tendencies were qualitatively in good agreement with the observed warming trends. The features of the daily variation, such as larger warming during the night and smaller warming during the day, were also in good agreement with observations. The correlation factors, however, showed only weak concordance between the simulation and the observation.

First, the discrepancy between the analytical methods used in the simulation and for the observations should be recognized. The warming results from the simulation were simple differences between sensitivity experiments that used the same initial and lateral boundary atmospheric conditions. On the other hand, the warming trends derived from the observations were calculated using regression analysis. As discussed in the sections on factor analysis and the nonlinear response of the

Fig. 12. Differences in radiative surface temperatures between the experiments of EXP2006HR and EXP2006H for the Tokyo grid. The radiative surface temperature was estimated from the surface temperatures of the roofs, walls, and the ground as defined in the urban canopy scheme. The dotted and solid lines represent the summer and winter cases, respectively.

atmosphere, atmospheric stability affects the vertical mixing of heat fluxes. Therefore, there might be easily warmed years and insensitive years. We

should keep in mind that the observational trends involve such large-scale interannual variations.

Furthermore, there is probably some room to discuss the applicability of the base settings listed in Table 3 for representing each type of land use in 1976, although the parameters are well optimized and are used presently for operational predictions at the JMA. Although we tried to use datasets of anthropogenic heat and building shapes as real as possible for the 2006 simulations, the settings of those for 1976 are a matter of speculation.

For more precise reproduction, we had to down-scale using various reanalysis datasets, for example, of JRA-25 (Onogi et al. 2007), as initial and lateral boundary conditions and had to perform numerical integrations over several decades. As no release of anthropogenic heat was assumed in the 1976 study, the effects of anthropogenic heat were probably overestimated. The considerable overestimation for Tokyo seemed to be caused by overestimation of the anthropogenic heat effect. This can be explained by the larger discrepancy in the winter case. We assumed that there was no anthropogenic heat in 1976, but there already could have been a certain amount of heat loaded in a megacity such as Tokyo. On the other hand, the overestimation at Takada in the summer case seemed to be caused by the land use effect. This can be explained by

Fig. 13. Scatter plots between the temperature differentials of (EXP2006HR-EXP2006H) and (EXP2006R-EXP2006). These differentials both represent the warming effects of the building aspect ratio changes. Open circles are the grids without any anthropogenic heat in the simulations. Closed circles are the grids onto which anthropogenic heat was loaded.

Fig. 14. Horizontal distributions of the overheated grids (closed circles in Fig. 12). The vectors represent the 2 months' averaged vectors of the surface winds at 10 m. The contour lines represent the advection term of the potential temperature at the lowest atmospheric level.

the fact that discrepancy from the observed trend was only observed in the summer case. Actually, the Takada meteorological observatory has larger premises than other typical observatories, with many trees along with a nearby stream, although it is surrounded by urban land. Such a local environment could be a cause of the large difference between the simulation and the observation. This could be a possible limitation of this study.

The area fraction changes of the land use categories over the 30-year period showed a positive impact on the surface air temperature. The warming effect seemed to be mainly caused by the decrease of vegetation. This could be explained by the well-known Bowen ratio effect. The simulations confirmed that the Bowen ratio effect is larger in a moist and sunny summer than in a dry winter with weak sunshine. From this analogy, this kind of warming effect should be larger in western Japan, where it is humid, than in drier northern Japan. Furthermore, from the aspect of urban planning, the importance of keeping large green spaces is implied if we think that Japan will gain more features of a humid subtropical climate as global warming progresses in the future.

The impact of the anthropogenic heat was larger in winter than in summer. The sensitivity of the atmosphere to the input heat load was larger in winter (Fig. 11). This can be explained by the

inhibition of vertical mixing in the relatively stable atmosphere of winter seasons. However, in the winter case (Fig. 10), the effect of the anthropogenic heat load peaked in the evening and the warming range slightly decreased up through dawn even though the atmosphere must have become more stable during these hours. The decrease of the heat amount during the night by itself likely produced the evening peak. The largest peak in the morning can be explained by the combination of stable atmospheric conditions and the large heat amounts in that time range.

A proportional relation between the heat release and the warming effect can be seen in Fig. 11. There are a number of points, however, that obviously deviate from the average proportion. The gray squares in Fig. 14 show the grids of these overheated points (indicated by closed circles in Fig. 11). It can be seen that they appear in areas surrounding the centers of heat loads. The vectors in the figure show the direction of the average surface wind. The contour lines represent the advection terms of the potential temperature at the lowest atmospheric level, calculated from hourly data and averaged throughout the seasons. Overall, the urban area had negative heat advection. The overheated areas, however, correspond to the less-negative advection areas in both summer and winter. Considering the average wind field, the

advection of relatively warm air from the upwind urban area can be one cause of overheating in summer. In winter, the locally larger heat loads in the midwest part of Tokyo, where some bedroom suburbs lie along trunk railways, form the less-negative advection areas around them, although there exist less densely urbanized grids in the upwind area of the overheated grids under the northerly prevailing wind.

We arrived at the possibility that the temperature rise was caused by the increase in the building aspect ratio from the simulations. The main factor appears to be the temperature rise of the urban surfaces. The effect of the surface warming during the night was larger than the effect of surface cooling during the daytime. The total effect was larger in winter, when nights are relatively longer, than in summer. From this hypothesis, the effect of the aspect ratio changes should be larger in northern Japan because the nighttime is relatively longer there than in other areas. The effect should also be larger in inland basins where radiative cooling occurs effectively.

6. Conclusions

By numerical simulations using the JMA-NHM, we studied how much 3 bottom boundary condition changes, namely, in land use area fraction, anthropogenic heat release, and increased building aspect ratio, could explain the warming trends observed at the AMeDAS stations during a 30-year period (1976–2006). Unlike previous sensitivity studies in which the simulations were executed under idealized or other typical atmospheric conditions, we tried to determine the warming effects of the land surface modifications on the average surface air temperature under many weather conditions through longer-time simulations.

From the differentials between simulations with 2 bottom boundary conditions emulating the land surfaces of 1976 and 2006, the possible sources of warming along with the urbanization were determined. The correlation coefficients between the simulated differentials and the observational trends at the grids of the AMeDAS stations showed a lower correlation (0.294 with a significance level of 90%) in the summer case and fairly good correlation (0.444 with a significance level of 99%) in winter.

A sensitivity study of land use modification, i.e., the spread of urban area, showed a warming effect on average, and that the effect was larger in grids

where the land use modification rate was larger. The effects were very small in central Tokyo because the urban area fraction was already saturated there by 1976. This effect was larger in summer when the Bowen ratio is originally small.

The warming effect of anthropogenic heat was concentrated to the central urban area where the heat was mainly loaded. The effect was larger in winter owing to relatively stable atmospheric conditions. Maximum warming was observed in the morning and a secondary peak was seen in the evening if we set the heat to vary realistically with time.

The increase of the aspect ratio of the buildings also had a warming effect on the surface air temperature. It was mainly caused by the inhibition of radiative cooling during nighttime, and the effect was larger in winter. The daily variation of this effect had a single peak in the morning.

Secondarily, the simulations in this study showed that there would be large discrepancies in the results depending on the settings of the bottom boundary conditions, although the dependency did not seem to affect the whole atmosphere system so much. The results of this study illustrate the importance of more precise land surface settings when we assess the environment of the surface layer, which is the most important layer for human activities.

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References

- Beljaars A. C. M., and A. A. M. Holtslag, 1991: Flux parameterization over land surface for atmospheric models. *J. Appl. Meteor.*, **30**, 327–341.
- Adachi S., and F. Kimura, 2010: A factor analysis on the nighttime warming trends in the Kanto area of Japan. *J. Jpn. Study Group Clim. Impact Appl.*, **28**, 5–13 (in Japanese).
- Aoyagi T., and N. Seino, 2011: A square prism urban canopy scheme for the NHM and its evaluation on summer conditions in the Tokyo metropolitan area, Japan. *J. Appl. Meteor. Climatol.*, **50**, 1476–1496.

- ECCJ, 2005: Report of survey on the effect of energy conservations to mitigation of heat island phenomena. Energy Conservation Center Japan, 266 pp (in Japanese).
- Fujibe F., 1994: Long-term falling trends of pressure over the Kanto Plain as evidence of increasing heat content in the lower atmosphere in the daytime of the warm season. *J. Meteor. Soc. Japan*, **72**, 785–792.
- Fujibe F., 2003: Long-term surface wind changes in the Tokyo metropolitan area in the afternoon of sunny days in the warm season. *J. Meteor. Soc. Japan*, **81**, 141–149.
- Fujibe F., 2009: Detection of urban warming in recent temperature trends in Japan. *Int. J. Climatol.*, **29**, 1811–1822.
- Fujibe F., 2010: Urban warming in Japanese cities and its relation to climate change monitoring. *Int. J. Climatol.*, **31**, 162–173.
- Hara M., H. Kusaka, F. Kimura, and Y. Wakazuki, 2010: Effect of global climate change on urban heat island intensity of Tokyo metropolitan area—winter season case—. *Nagare*, **29**, 353–361 (in Japanese with English abstract).
- Hara T., 2008: Radiation Processes. *Separate volume of annual report of NPD*, **54**, 133–137 (in Japanese).
- Ichinose T., K. Shimodozono, and K. Hanaki, 1999: Impact of anthropogenic heat on urban climate in Tokyo. *Atmos. Environ.*, **33**, 3897–3909.
- Inoue T., and F. Kimura, 2004: Urban effects on low-level clouds around the Tokyo metropolitan area on clear summer days. *Geophys. Res. Lett.*, **31**, L05103, doi:10.1029/2003GL018908.
- Inoue T., and F. Kimura, 2007: Numerical experiments on fair-weather clouds forming over the urban area in northern Tokyo. *SOLA*, **3**, 125–128.
- IPCC, 2007: Climate change 2007: The physical science basis. In contribution of working group I to the fourth assessment report of the IPCC, Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K., Tignor M., Miller H. L. (eds). Cambridge University Press: New York; 1056 pp.
- Ishida J., 2008: The governing equations of the JMA-NHM and the implementation of the hybrid terrain following vertical coordinates. *Separate volume of annual report of NPD*, **54**, 27–43 (in Japanese).
- Ishizaki N., and I. Takayabu, 2009: On the warming events over Toyama Plain by using NHRCM. *SOLA*, **5**, 129–132.
- Kawase H., T. Yoshikane, M. Hara, F. Kimura, T. Yasunari, B. Ailikun, H. Ueda, and T. Inoue, 2009: Intermodel variability of future changes in the Baiu rainband estimated by the pseudo global warming downscaling method. *J. Geophys. Res.*, **114**, D24110, doi:10.1029/2009JD011803.
- Kikegawa Y., Y. Genchi, H. Yoshikado, and H. Kondo, 2003: Development of a numerical simulation system toward comprehensive assessments of urban warming countermeasures including their impacts upon the urban building's energy demands. *Appl. Energy*, **76**, 449–466.
- Kimura F., and S. Takahashi, 1991: The effects of land-use and anthropogenic heating on the surface temperature in the Tokyo metropolitan area: A numerical experiment. *Atmos. Environ.*, **25B**, 155–164.
- Kitagawa H., 2000: Radiation Processes. *Separate volume of annual report of NPD*, **46**, 16–31 (in Japanese).
- Kusaka H., F. Kimura, H. Hirakuchi, and M. Mizutori, 2000: The effects of land-use alteration on the sea breeze and daytime heat island in the Tokyo metropolitan area. *J. Meteor. Soc. Japan*, **78**, 405–420.
- Kusaka H., H. Kondo, Y. Kikegawa, and F. Kimura, 2001: A simple single-layer urban canopy model for atmospheric models: Comparison with multi-layer and slab models. *Bound.-Layer Meteor.*, **101**, 329–358.
- Kusaka H., and F. Kimura, 2004a: Coupling a single-layer urban canopy model with a simple atmospheric model: Impact on urban heat island simulation for an idealized case. *J. Meteor. Soc. Japan*, **82**, 67–80.
- Kusaka H., and F. Kimura, 2004b: Thermal effects of urban canyon structure on the nocturnal heat island: Numerical experiment using a mesoscale model coupled with an urban canopy model. *J. Appl. Meteor.*, **43**, 1899–1910.
- Kusaka H., T. Takata, and Y. Takane, 2009: Reproducibility of regional climate in central Japan using the 4-km resolution WRF model. *SOLA*, **6**, 113–116.
- Masson V., 2000: A physically-based scheme for the urban energy budget in atmospheric models. *Bound.-Layer Meteor.*, **94**, 357–397.
- Ohashi Y., Y. Genchi, H. Kondo, Y. Kikegawa, and Y. Hirano, 2007: Influence of air-conditioning waste heat on air temperature in Tokyo during summer: Numerical experiments using an urban canopy model coupled with a building energy model. *J. Appl. Meteor. Climatol.*, **46**, 66–81.
- Onogi K., J. Tsutsui, H. Koide, M. Sakamoto, S. Kobayashi, H. Hatsushika, T. Matsumoto, N. Yamazaki, H. Kamahori, K. Takahashi, S. Kadokura, K. Wada, K. Kato, R. Oyama, T. Ose, N. Mannoji, and R. Taira, 2007: The JRA-25 reanalysis. *J. Meteor. Soc. Japan*, **85**, 369–432.
- Saito K., J. Ishida, K. Aranami, T. Hara, T. Segawa, M. Narita, and Y. Honda, 2007: Nonhydrostatic atmospheric models and operational development at JMA. *J. Meteor. Soc. Japan*, **85B**, 271–304.

- Senoo H., M. Kanda, T. Kinouchi, and A. Hagishima, 2004: Estimation of anthropogenic heat and vapor emission, and the impact on local meteorology. *Ann. J. Hydr. Eng., JSCE*, **48**, 160–174 (in Japanese with English abstract).
- Tokyo Metropolitan government, 1977: A summary of urban planning 1976 (Toshi Keikaku Gaiyou 1976). Tokyo Metropolitan government, 336 pp. (in Japanese).
- Yabu S., S. Murai, and H. Kitagawa, 2005: Clear-sky radiation scheme. *Separate volume of annual report of NPD*, **51**, 53–64 (in Japanese).