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REGIONAL WARMING RELATED TO LAND USE CHANGE DURING RECENT 135 YEARS IN JAPAN

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Abstract

LUIS (Land Use Information System) is a digital land use data set covering all Japan with 2-km grid cells. The land use on each grid cell in circa 1850, circa 1900, circa 1955, and circa 1985 was compiled in LUIS. By the numerical simulations with a mesoscale climate model (CSU-MM) referring to LUIS, the author attempted to pick up the influence on surface air temperature by regional warming related to land use change during recent 135 years. During four stages, the area showing the regional warming related to land use change has expanded. This feature was significant around Tokyo and Osaka. Urbanization during four stages weakened the daytime penetration of sea breeze in the south Kanto Plain (around Tokyo) and it brought a regional warming. The warming area moved to north with expanding on the Kanto Plain by sea breeze since daytime till mid-night. In the Osaka Plain the movement of warming area by sea breeze was smaller than in the Kanto Plain. The daily maximum and minimum temperature in c. 1850, estimated from observed data (monthly averages of daily maximum and minimum temperature) in Tokyo (Otemachi) since 1876, were compared with computed results. The computed daily maximum temperature agreed well with the estimated value.

KEYWORDS: *warming, urbanization, numerical simulation, land use, historical climatology*

1. Introduction

Only about 120 years have passed since the beginning of meteorological observations in Japan, and researchers have used a variety of methods to reconstruct climate prior to then. A representative method involves the sustained effort of ascertaining the climate of historical ages from the notations about weather and the like found in the ancient documents and journals from around the country. Especially since near-modern times the Japanese have left many usable records, and, although of a qualitative nature, researchers have been learning how hot in summer, or how cold in winter, it was in those days (Mikami, 1996). But these records do not cover all of Japan, and their information contains many temporal and spatial lacunae.

Now, however, the progress in meteorological models and computers makes it possible to compute local wind systems and surface air temperature distributions if one knows land use distributions and other detailed surface boundary conditions (Kimura and Takahashi, 1991; Ichinose *et al.*, 1999). Land use data obtained by dividing all of Japan into 2-km-square grid cells at four stages (c. 1850, c. 1900, c. 1950, c. 1985; the Land Use Information System, or LUIS, which was digitally

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published by UNEP/GRID-Tsukuba) are available to researchers, and they revealed the following two major characteristics about land use change in the Chubu Region between c. 1850 and c. 1985: 1) Expansion of urbanized area in the south Kanto Plain and other plains, and 2) recovery of forests in the Chubu mountainous areas (Himiyama, 1995). It is anticipated that such large-scale surface changes bring about localized climate changes owing to changes in the surface heat budget. It seems likely that if one inputs past land use distribution into a mesoscale climate model as the surface boundary conditions, it would be possible to reproduce the wind systems and surface air temperature distributions that could have appeared at past stages.

To do this, the model needs representative observed values (ex. air temperature) to use as the initial values for computing, and to validate computed results. The network of weather stations and other observation facilities that has been established throughout Japan since the latter half of the 19th century (1876) provides information on long-term temperature fluctuations to the present day. Data for Tokyo in particular have often been used to ascertain changes in urban climate occurring in conjunction with urbanization (Yoshino, 1990/1991). There are also many findings on global warming (Jones, 1988) and other air temperature changes that have occurred over broader areas and longer times than those induced by local land use changes (Maejima *et al.*, 1980), and comparing them to the chronological changes in computed air temperatures will perhaps be necessary to elucidate the contribution of land use change to climate change in Japan. Comparisons like this will also help show ways to solve the problem of the temporal and spatial discontinuity of data in historical climatology.

Such methods are highly significant for one more reason. The impact of urbanization in Japan's big cities is a diachronic temperature rise on the order of 1°C per century (Fujibe, 1995). Until now people have relied on statistical methods (Park *et al.*, 1994) in an effort to distinguish between two influences on surface air temperature observations: the influence of localized warming caused by urbanization, and the influence of global warming and other broader-area's air temperature changes, but of course such methods are inapplicable for regions and time periods that have no observed data. Much pioneering research has eliminated the influence of urbanization as noise when estimating temperature changes over larger areas (Kukla *et al.*, 1986). But if, by providing a mesoscale model with past land use distributions as surface boundary conditions, the author establishes a method to simulate local wind systems and surface air temperature distributions that could have occurred at certain past stages, it would perhaps help find a way to distinguish between the influence of localized warming caused by urbanization, and the influence of global warming and other broader-area's air temperature fluctuations even for regions and time periods with no observed data.

Case studies on the upstream of the Rhine River in 1710 (Lenz, 1996), on Edo (Tokyo was called "Edo" up to the middle of the 19th century.) in the first half of the 19th century, and others are examples of similar computings performed from the perspective of quantifying the influence of urbanization-induced changes in the surface heat budget on surface air temperature distribution and wind systems, as opposed to research from a historical climatology perspective. Researchers prepared land use distributions for the time periods in question from old maps and other sources. And because the time periods predate the beginning of meteorological observations, there are no comparisons with observed meteorological data.

This study therefore conducted numerical simulations of surface air temperature distributions and wind systems using a mesoscale model supplied with the aforementioned land use information

(Himiyama, 1995), and attempted to quantify local climate change brought about by changes in land use since near-modern times.

2. Preparation of Land Use Information

When conducting the numerical simulations it is necessary to translate the land use data mentioned above into surface parameters. With reference to Anthes *et al.* (1987), Ichinose *et al.* (1999) assigned six surface parameters (albedo, evaporation efficiency, roughness length, density (density of material covering the ground), specific heat capacity, heat diffusion coefficient) for rice paddies, vegetable fields, orchards, lawns and parks, forests, yards, built-up areas, traffic use, other use, and surface water. In this study the author determined the type of land use at the upper left grid point of each 2-km cell to be that judged closest to one of the 10 land use categories listed above, translated that into the surface parameters, and applied the weighted averages to a grid with 10-km cells, i.e., horizontal grid cells for the following numerical simulations.

Urbanized areas (i.e., built-up areas and traffic use) were assumed to have anthropogenic heat. Diurnal change (Ichinose *et al.*, 1999) was assigned with c. 1985 having a daily average of 25 W m^{-2} (The maximum was around 40 W m^{-2} and the minimum was around 5 W m^{-2}.). For c. 1955, c. 1900, and c. 1850 the author set the intensities that were, respectively, 75%, 50%, and 25% of that in c. 1985.

3. Mesoscale Model Overview

The numerical simulation model used in this study was based on the Colorado State University Mesoscale Model (CSU-MM) (Pielke, 1974) with some modifications (Ulrickson and Mass, 1990; Kessler and Douglas, 1992) and with small changes to input values for several surface boundary conditions like albedo or anthropogenic heat in each grid cell (Ichinose *et al.*, 1999). Hydrostatic equilibrium and the Boussinesq approximation are assumed in this model. The model consists of equations of motion, moisture, and continuity within a 3-dimensional terrain-following coordinate system and it includes a thermodynamic equation, a diagnostic equation for pressure, and an equation for surface heat budget. This model was used to compute for square regions of several hundred km on a side and covering the environs of five big Japanese cities (Sapporo, Sendai, Tokyo, Osaka, Fukuoka) at four stages for which land use data existed (Figure 1).

Often attempted using old journals and other written sources are studies of rainfall (Ogasawara, 1990) and cloudiness, which are easy to reconstruct even from qualitative descriptions. Because CSU-MM does not incorporate the water vapor condensation process, it does not allow simulations on rainfall and cloudiness. Additionally, simulating synoptic pressure fields and the prevailing wind systems that arise in conjunction with them is impossible for a mesoscale model alone. Because cloudless (Yamazoe and Ichinose, 1994), weak breezes (Fujino *et al.*, 1994), and the like are known as meteorological conditions under which heat islands become pronounced, it follows that the influence of land use on surface air temperature distribution and wind systems tends to appear under calm and clear conditions when winds are weak. Further, it is by way of heat stress and during summers that higher city temperatures caused by urbanization make life unpleasant for people.

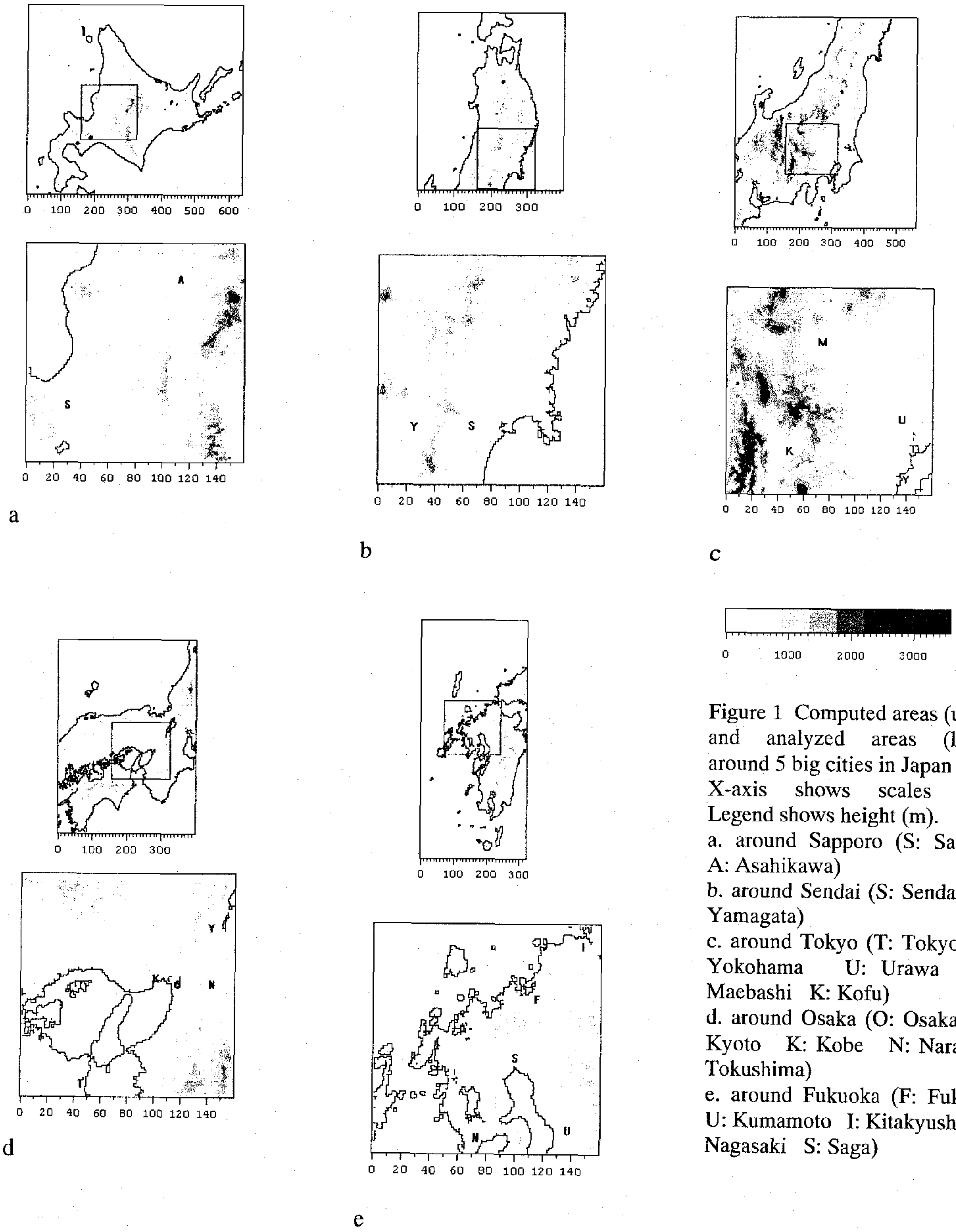


Figure 1 Computed areas (upper) and analyzed areas (lower) around 5 big cities in Japan X-axis shows scales (km). Legend shows height (m).
a. around Sapporo (S: Sapporo A: Asahikawa)
b. around Sendai (S: Sendai Y: Yamagata)
c. around Tokyo (T: Tokyo Y: Yokohama U: Urawa M: Maebashi K: Kofu)
d. around Osaka (O: Osaka Y: Kyoto K: Kobe N: Nara T: Tokushima)
e. around Fukuoka (F: Fukuoka U: Kumamoto I: Kitakyushu N: Nagasaki S: Saga)

For these reasons the author set his computing dates to the 48 hours (calm and clear condition assumed) from 0 AM on July 26 of each stage, but analyzed results only from the 24-hour period beginning at 0 AM on July 27 to help ensure the stability of computed results. The time step for numerical integration was chosen as 60 s. The vertical coordinate system was same with Ichinose *et al.* (1999). The sea surface temperature and the initial value for surface air temperature (ground surface temperature also) were fixed at 18°C (Sapporo environs), 22°C (Sendai environs), 25°C (Tokyo environs), 25°C (Osaka environs), and 26°C (Fukuoka environs) for all four stages. It would be necessary to vary these values when trying to include the effects of global warming and other factors, but as the purpose of this study was to determine the influence of urbanization, fixing the values excluded the effects of factors such as global warming. Other initial values were 1,000 hPa for surface air pressure, 5.5 K km^{-1} for the vertical gradient of potential temperature, 70.0% for surface relative humidity, and S 0.5 m s^{-1} for wind direction and velocity in all layers. Additionally, lateral boundary conditions were assumed zero-gradient.

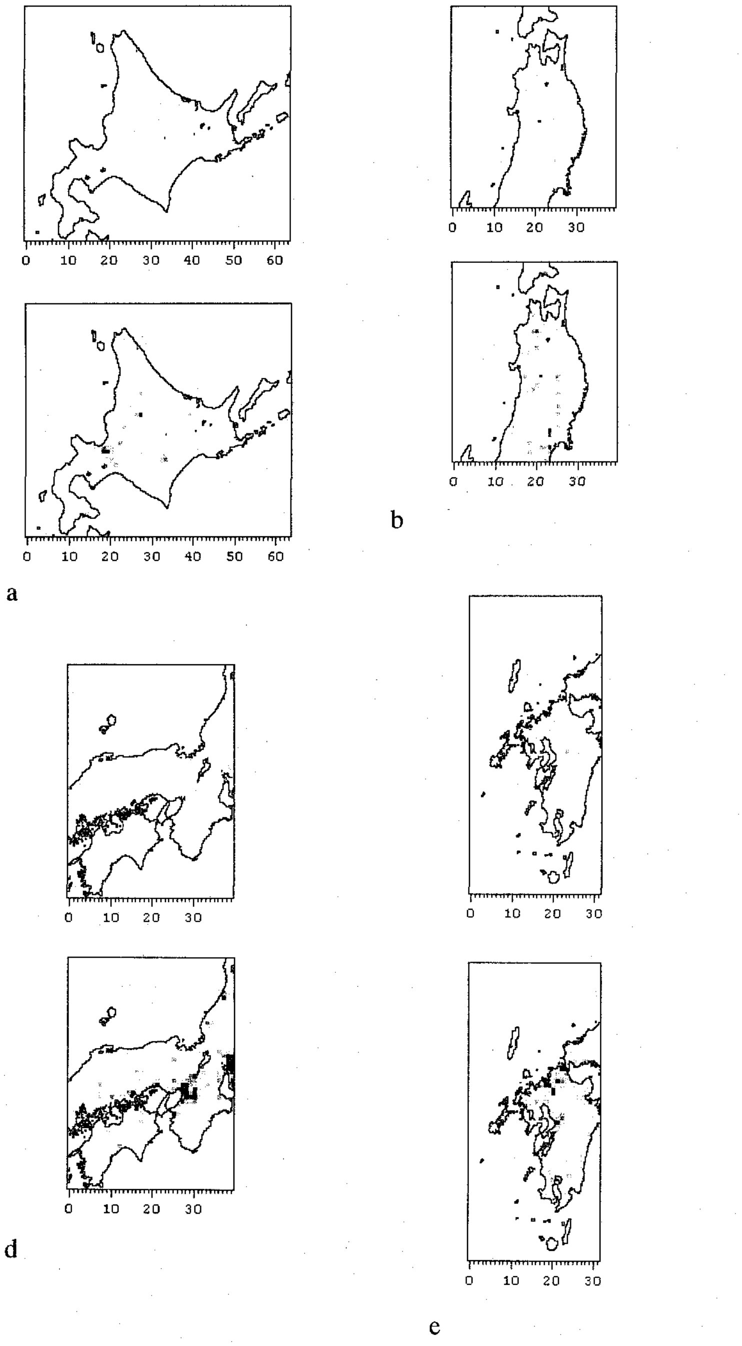
4. Land Use Change since Near Modern Times in the Computed Regions

Urbanization advanced in the five big cities' environs during all four stages (Figure 2). Urbanization around Tokyo and Osaka was especially pronounced. In order to ascertain the general trends in land use change during the years covered, the author compiled the increases and decreases in the land use ratios for c. 1850 and c. 1985 in the five computed regions (Table 1). A comparison of the two stages showed a pronounced decrease in rough land in mountainous zones and pronounced expansion of urbanized areas in the plains. It was anticipated that expanding urbanized areas around Tokyo, Osaka, and Fukuoka would bring about localized rises in air temperature.

5. Results of Computings of Surface Air Temperature Distribution and Wind Systems

5.1 Computed Results for the Tokyo Environs

From among the numerical model outputs, this study examined the air temperature and horizontal wind distribution at 7.5 m above ground level, and their diurnal variabilities. The following examples showed surface air temperature distributions (Figure 3) and surface wind systems (Figure 4) in every six hours (3 AM, 9 AM, 3 PM, 9 PM) in the Tokyo environs at c. 1985. In order that the analysis would focus on the development and decline process of sea breezes, the author put 3 AM after 9 PM. Convergence of computed results was confirmed by comparing air temperatures obtained at the 24th and 48th hours after starting computings. Also shown are the differences in air temperature (Figure 5) and wind vectors (Figure 6) at c. 1850 and c. 1985.



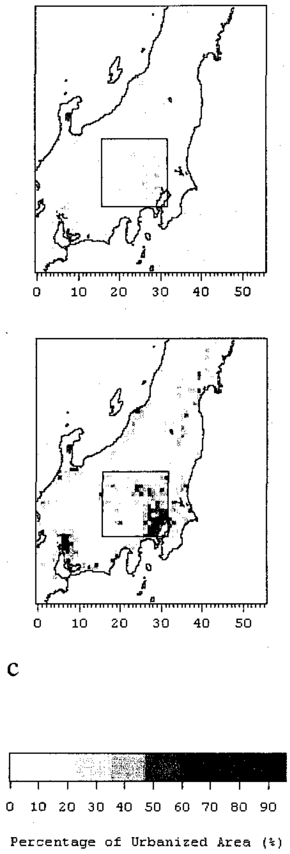


Figure 2 Urbanization around 5 big cities in Japan
Percentages of urbanized area in circa 1850 (upper) and in circa 1985 (lower) were shown.
X-axis shows scales (10km). Urbanization in the analyzed area around Tokyo was noticeable.
a. around Sapporo
b. around Sendai
c. around Tokyo
d. around Osaka
e. around Fukuoka

Table 1 Land use change in computed areas around 5 big cities in Japan (%)

a

around Sapporo	circa 1850	circa 1985	budget
Paddy Field	1.1	9.0	+7.9
Dry Field	0.0	8.3	+8.3
Orchard etc.	3.8	1.6	-2.2
Forest	86.7	65.1	-21.6
Rough Land	6.8	8.6	+1.8
Urbanized Area	0.0	5.6	+5.6

b

around Sendai	circa 1850	circa 1985	budget
Paddy Field	13.7	16.1	+2.4
Dry Field	5.0	3.2	-1.8
Orchard etc.	0.4	1.8	+1.4
Forest	61.3	64.4	+3.1
Rough Land	16.9	4.0	-12.9
Urbanized Area	1.6	9.3	+7.7

c

around Tokyo	circa 1850	circa 1985	budget
Paddy Field	12.0	9.0	-3.0
Dry Field	14.9	6.2	-8.7
Orchard etc.	0.2	4.8	+4.6
Forest	54.4	53.8	-0.6
Rough Land	12.1	2.5	-9.6
Urbanized Area	4.9	21.8	+16.9

d

around Osaka	circa 1850	circa 1985	budget
Paddy Field	18.9	11.9	-7.0
Dry Field	3.7	1.7	-2.0
Orchard etc.	2.0	3.0	+1.0
Forest	58.6	61.2	+2.6
Rough Land	12.4	2.2	-10.2
Urbanized Area	2.3	17.4	+15.1

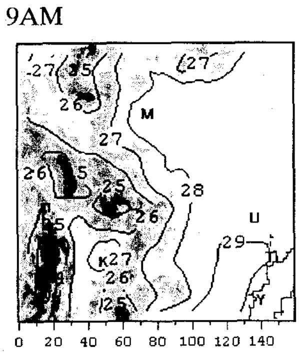
e

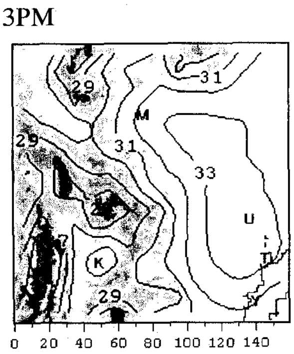
around Fukuoka	circa 1850	circa 1985	budget
Paddy Field	21.9	18.4	-3.5
Dry Field	9.2	3.5	-5.7
Orchard etc.	1.3	8.8	+7.5
Forest	44.7	45.6	+0.9
Rough Land	18.2	3.7	-14.5
Urbanized Area	3.6	18.4	+14.8

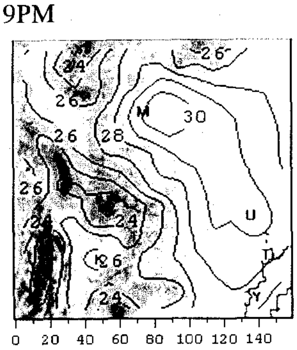
At 9 AM there was a high-temperature region of 29°C and above stretching from Tokyo to Yokohama (Figure 3). The air temperature differences between the two stages were at least +0.3°C in the south Kanto Plain, and at least +0.7°C in central Tokyo (Figure 5).

At 3 PM there was an area of at least 33°C over the Kanto Plain stretching from central Tokyo to Maebashi (Figure 3). In the south Kanto Plain there was sea breeze penetration while in mountainous zones valley breezes arose, but they were independent of one another (Figure 4). Temperature differences at the two stages were at least +0.4°C in the south Kanto Plain, and at least +1.2°C near the Tokyo Bay (Figure 5). Of interest regarding the difference between wind vectors at the two stages is the development of a wind system (around 1 m s^{-1}) that converged in central Tokyo (Figure 6). This change is thought to have been caused by the higher temperature in central Tokyo. Farther inland from central Tokyo there was a directional change that attenuated sea breezes. Yoshikado (1994) also pointed out instances in which the formation of heat islands in cities located along the coast impeded the inland penetration of sea breezes. Even in the north Kanto Plain there was a region of +0.4°C or higher (Figure 5).

At 9 PM a pronounced high-temperature region had formed over the Kanto Plain, and it was distinct especially around Maebashi (Figure 7). The Kanto Plain was covered by a southerly wind system (Figure 4). An increased-temperature region of +0.3°C or higher crossed mountain passes and spread into an inland basin (the Ueda Basin) (Figure 5). Temperature differences were at least +1.1°C







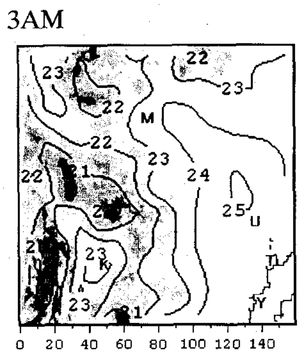


Figure 3 Surface air temperature (°C) in a calm and clear day in late July around Tokyo in circa 1985
Legend is common with Fig. 1c.

in the central Kanto Plain and at least +1.9°C in the south of Urawa. Compared to 3 PM, the region of a southerly wind system moved north and expanded considerably (Figure 4). Changes up to this phase appeared to be caused by the development of an extended sea breeze (Kondo, 1990), and the northward shift of the increased-temperature region over the Kanto Plain as it expanded (Figure 5).

At 3 AM the high-temperature core (Figure 3) and its attendant convergence field remained on the central Kanto Plain (Figure 4) as the high-temperature field weakened. Mountain breezes prevailed in the hills surrounding the plains. High temperatures of at least +0.2°C around Maebashi and at least +0.6°C in the south Kanto Plain were observed (Figure 5).

5.2 Comparison of Diurnal Variability at Two Stages

The author compared the diurnal variability in computed air temperature at the two stages in the cells that contained meteorological observatories which were located near the centers of the five big cities (Figure 8). In the four cities excepting Sapporo, air temperature difference as an effect of urbanization became gradually more pronounced during the forenoon, and was clearly manifested from about the time that the maximum temperature was attained until about midnight. Table 2 presented the comparison results for the two stages for the five big cities. Effect on surface air temperature on a calm, clear summer day was prominent in Tokyo and Osaka, which was commensurate with their scale of urbanization. Also interesting is that in the four cities excluding Sapporo, temperature differences between the two stages were maximum at 9 PM (1.8 °C in Tokyo, 2.2 °C in Osaka) and minimum at 6 AM, and reached their extremes at about the same time.

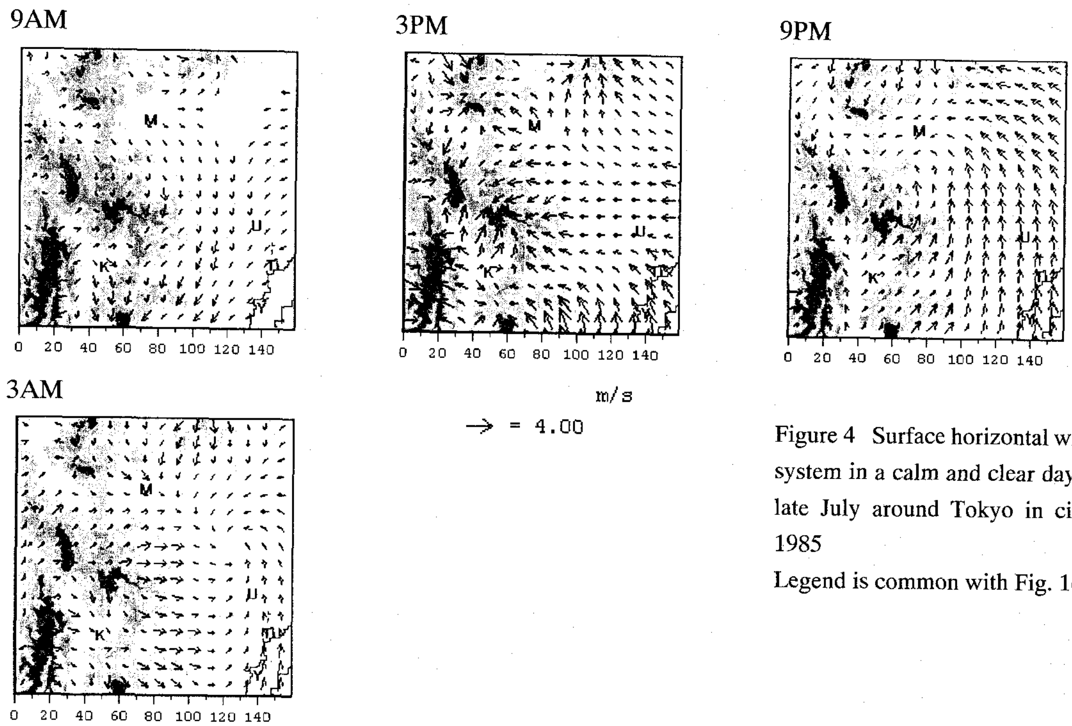


Figure 4 Surface horizontal wind system in a calm and clear day in late July around Tokyo in circa 1985
Legend is common with Fig. 1c.

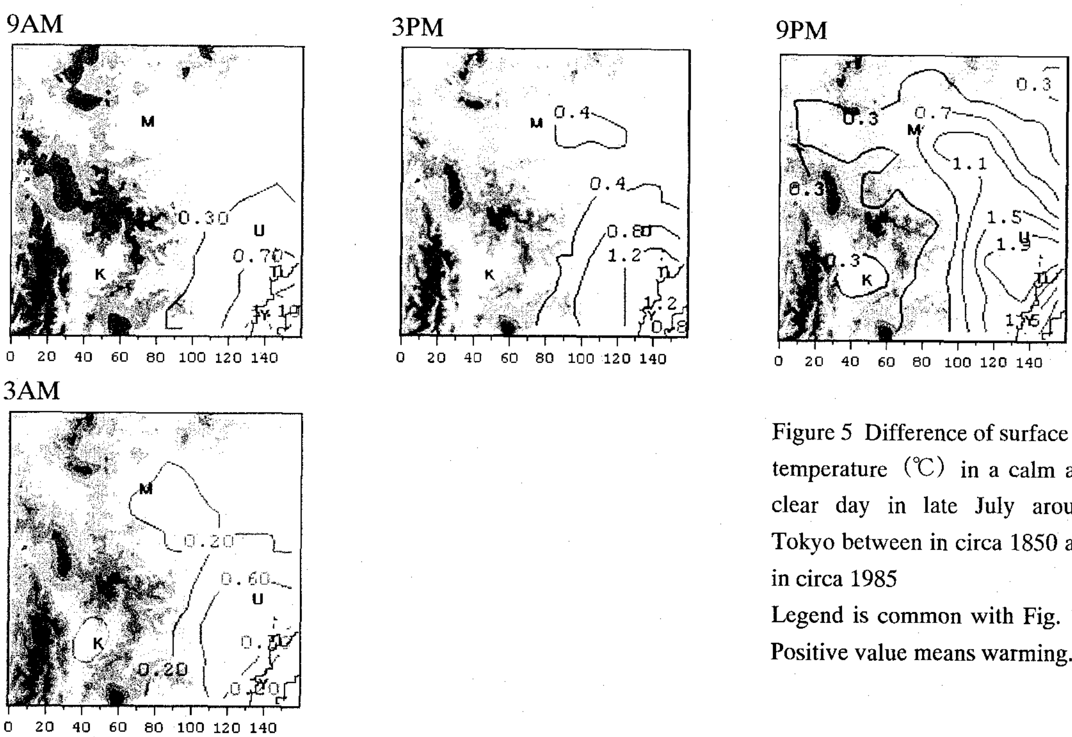


Figure 5 Difference of surface air temperature (℃) in a calm and clear day in late July around Tokyo between in circa 1850 and in circa 1985
Legend is common with Fig. 1c.
Positive value means warming.

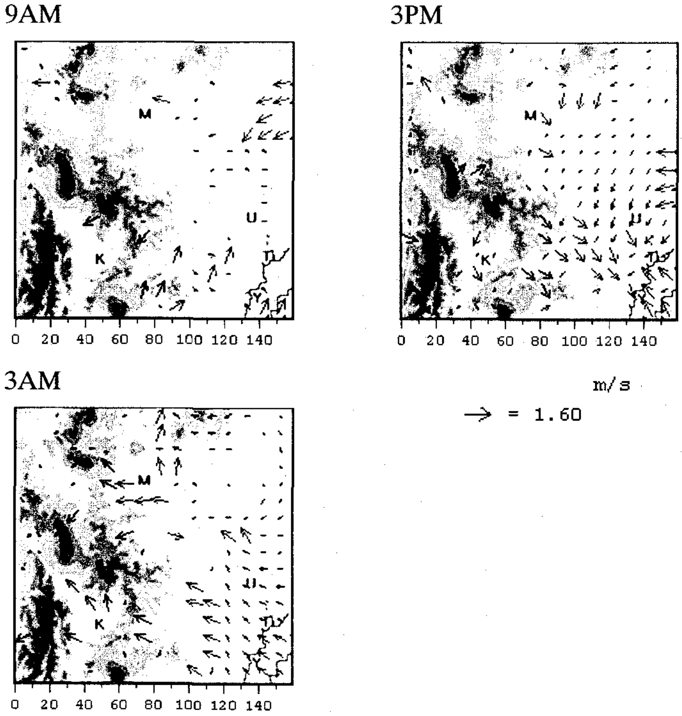


Figure 6 Difference of surface horizontal wind vectors in a calm and clear day in late July around Tokyo between in circa 1850 and in circa 1985
Legend is common with Fig. 1c.
Wind system was enforced in this direction.

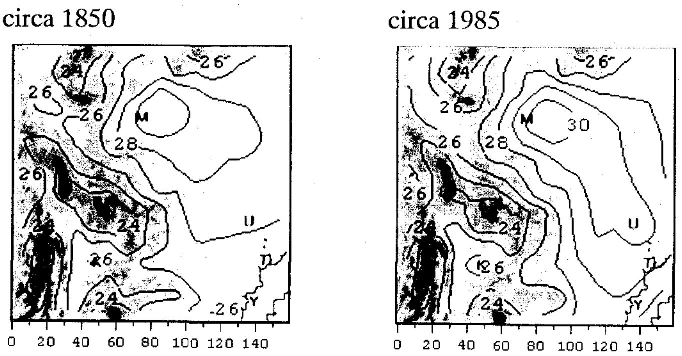
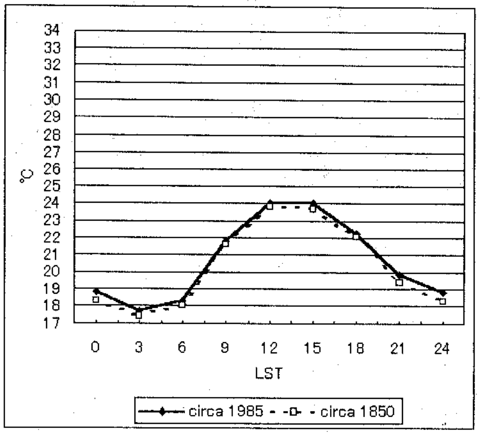


Figure 7 Warming at 9PM around Tokyo in a calm and clear day in late July (℃)
Legend is common with Fig. 1c.

a



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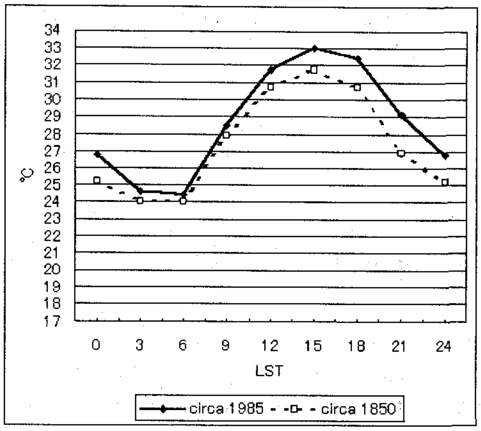

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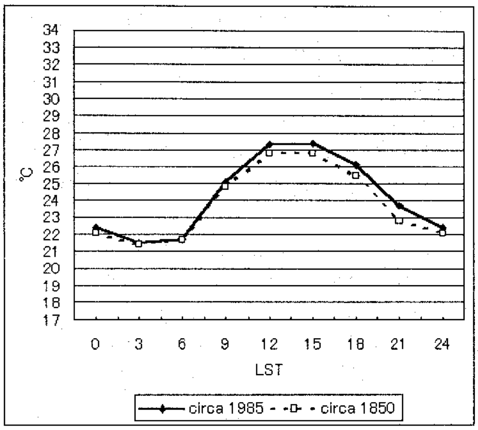

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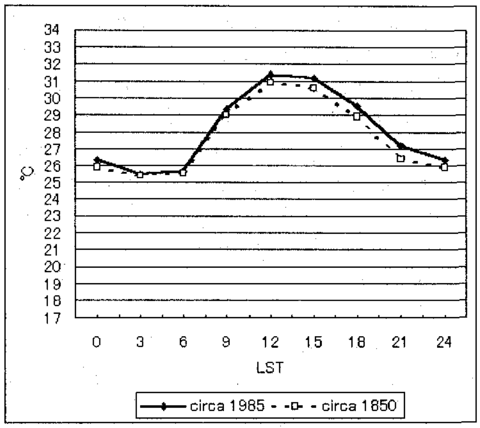

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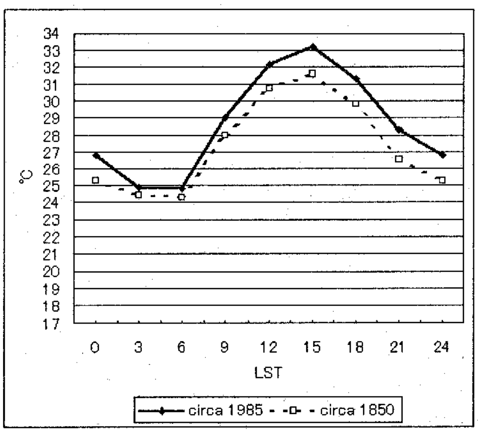


Figure 8 Diurnal variability of computed surface air temperature in a calm and clear day in late July in 2 stages

a. Sapporo b. Sendai c. Tokyo (Otemachi) d. Osaka e. Fukuoka

Table 2 Computed warming in a calm and clear day in late July related to land use change during recent 135 years (°C)

City	dTmax	at	dTmin	at
Tokyo	1.8	9PM	0.5	6AM
Osaka	2.2	9PM	0.4	6AM
Sapporo	0.5	0AM	0.2	9AM
Fukuoka	0.8	9PM	0.1	6AM
Sendai	0.9	9PM	0.0	6AM

dT=T(1985)-T(1850)

5.3 Computed Results for Environs of the Four Cities Other than Tokyo

1) Osaka

Just as around Tokyo, the Osaka environs exhibited diurnal variability in air temperature distribution (Figure 9) in conjunction with the change-off between sea and land breezes, and localized temperature increases (Figure 10) caused by urbanization.

At 3 PM the belt from Kyoto to Kobe was at least 32°C, and in Osaka it was at least 33°C (Figure 9). By contrast, there was a low-temperature region over the sea (the Kii Channel) offshore of Tokushima. The sea breeze blowing from the Osaka Bay into the Osaka Plain, and the sea breeze blowing from the Seto Inland Sea into the mountainous area to the north (the Chugoku Mountains) were characteristic. There were temperature increases of at least +0.2°C on the plains and at least +1.0°C around Osaka (Figure 10). In the low-lying area the wind system blowing toward the sea was strengthened, which made it hard for the sea breeze from the Osaka Bay to penetrate the belt between Kyoto and Kobe. One feature in common with the Tokyo environs is that in the Osaka Bay alone the sea breeze was slightly strengthened.

At 9 PM the belt from Kyoto to Nara was at least 29°C, and the Seto Inland Sea Region was at least 27°C (Figure 9). A wide-area sea breeze thought to come from the Pacific Ocean crossed the Kii Channel, blew over the Osaka Plain, and converged with the northward wind system found inland between Kyoto and Nara. Wind velocity over the Seto Inland Sea was relatively high. Higher temperatures (at least +2.4°C increase) were observed in concentric circles emanating from within Osaka, and the increase attained at least +1.6°C even in Nara (Figure 10). Just as at 3 PM, the increase was about +0.4°C in Kyoto, which was not affected by sea breezes. A characteristic change in the wind system was the strengthening of the mountain breeze in the Chugoku Mountains. Wind system changes hardly affected the temperature increase on the Osaka Plain.

At 3 AM the Osaka Plain became even cooler than part of the Seto Inland Sea (Figure 9), the increased-temperature region shrank (Figure 10), and it was about +0.6°C in the belt from Kyoto to Nara. Mountain breezes had arisen in the hills surrounding the plain (Figure 9), and a convergence zone appeared over the Seto Inland Sea.

Perhaps because local circulation, including sea breeze penetration, was smaller than in the Kanto Plain example, the increased-temperature region did not spread much inland. But the maximum temperature increase (difference between the two stages) in Osaka (+2.4°C) was larger than that in Tokyo (+1.9°C).

2) Fukuoka and Others

There were no large temperature increases in Fukuoka (Figure 11), Sendai (Figure 12), and Sapporo (Figure 13) as there were in Tokyo and Osaka between the two stages. And unlike Tokyo and Osaka, maximum-temperature regions and increased-temperature regions did not coincide. Examples for these three cities were shown only from 9 PM, when the difference between the two stages was marked.

During this time period temperatures were comparatively low at about 27℃ in Fukuoka and Kitakyushu, which lied along the Sea of Genkai, but there was an area of at least 28.5℃ in the neighborhood of Kumamoto. The wind blew inland from the Sea of Genkai. There were temperature increases of at least +0.6℃ in the area toward the inland region from Kitakyushu to Fukuoka, and around Kumamoto, and of at least +1.0℃ inside Fukuoka City between the two stages.

5.4 Effects of Forest Recovery

The lower-temperature regions in temperature comparisons between the two stages were mainly in the mountainous areas or at sea, but there was temporal and spatial variation. Almost all those regions were within -0.5°C, making cancellation by long-term temperature fluctuation over a broader area very possible. It was therefore difficult to attribute lower temperature to the effects of forest recovery.

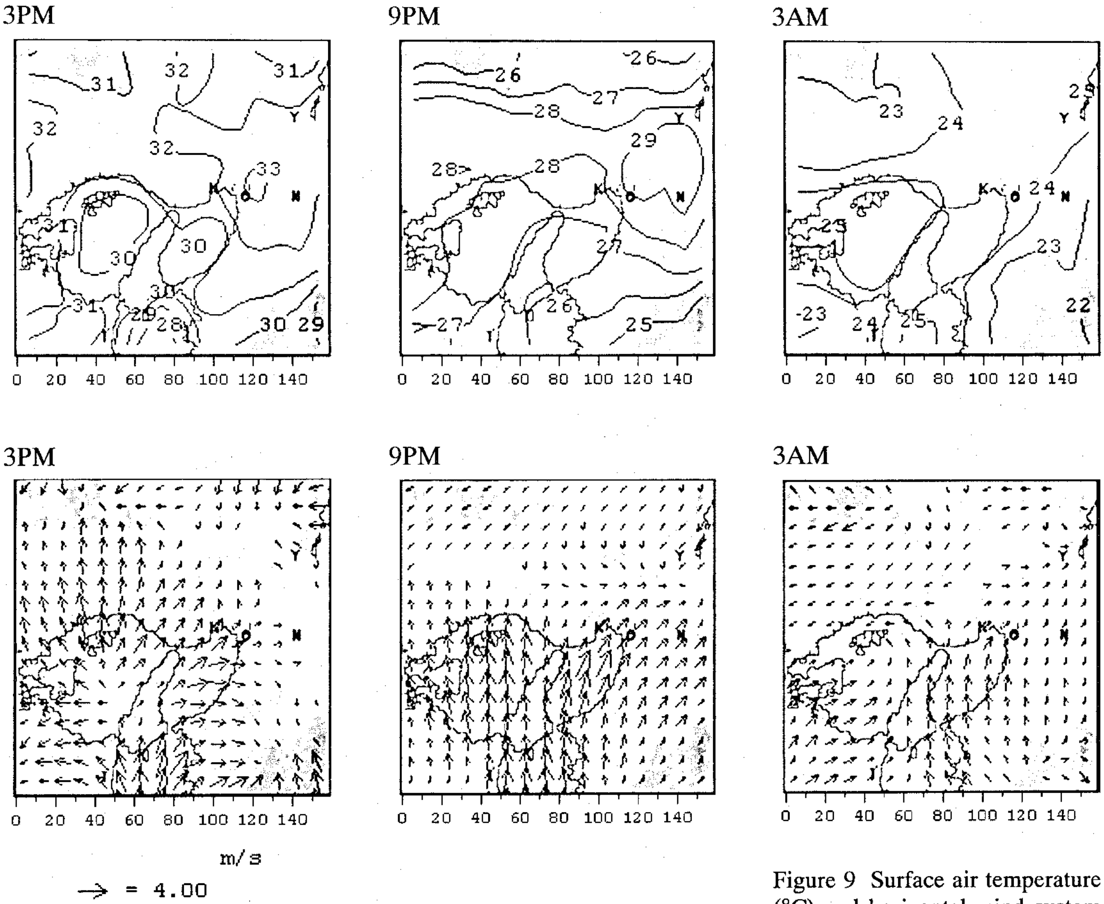
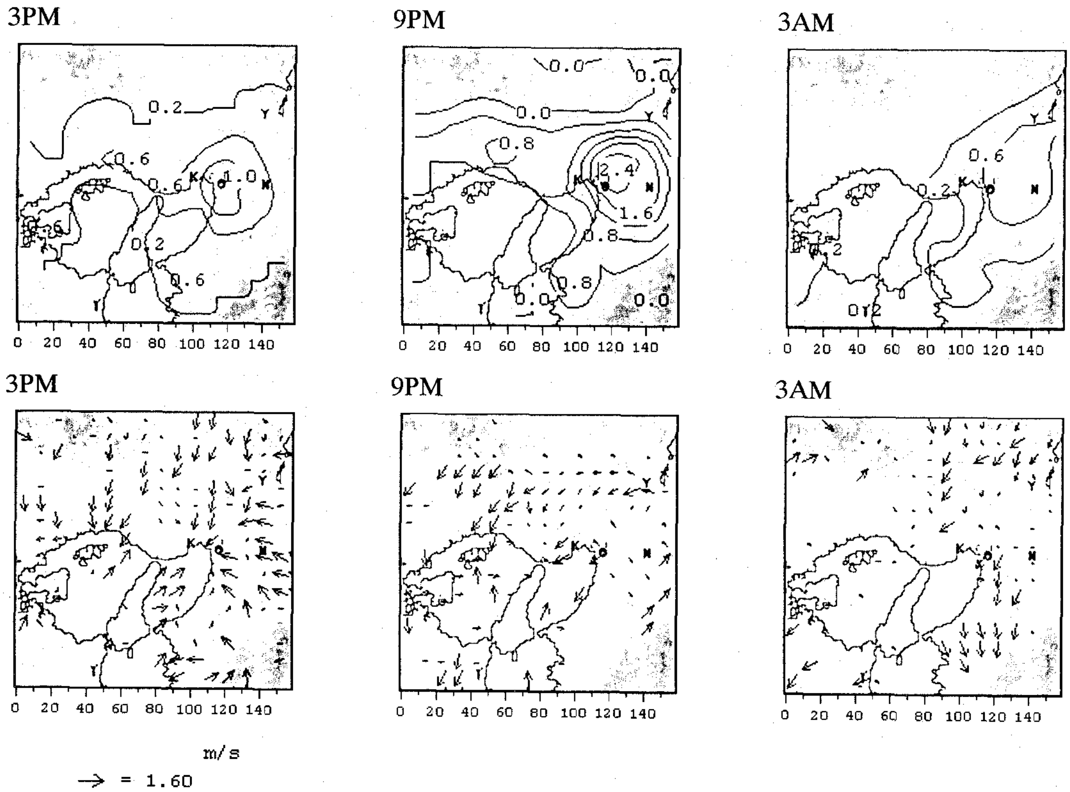
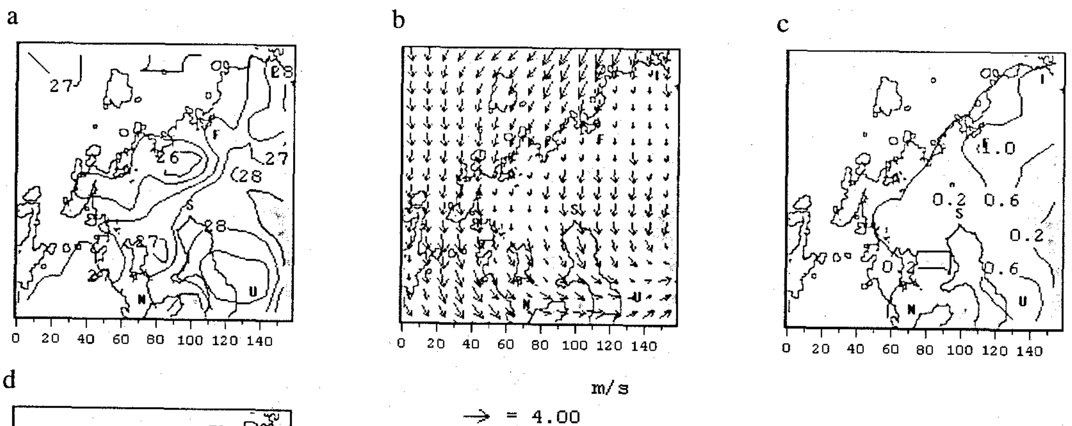
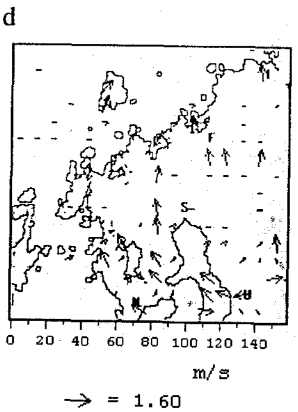


Figure 9 Surface air temperature (°C) and horizontal wind system in a calm and clear day in late July around Osaka in circa 1985 Legend is common with Fig. 1d.







Upper: Figure 10 Difference of surface air temperature (℃) and horizontal wind vectors in a calm and clear day in late July around Osaka between in circa 1850 and in circa 1985

Legend is common with Fig. 1d.

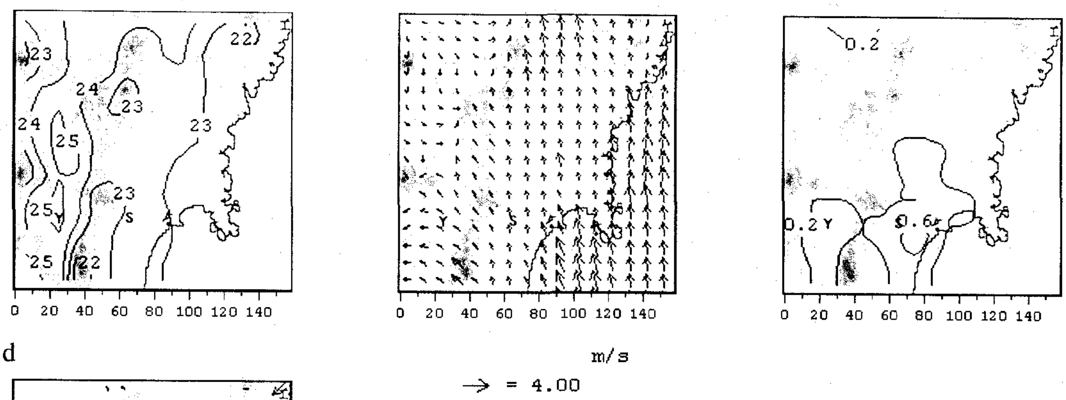
Lower: Figure 11 Computed results at 9PM in a calm and clear day in late July around Fukuoka

a. surface air temperature (℃)

b. surface horizontal wind system

c. difference of surface air temperature (℃) between in circa 1850 and in circa 1985

d. difference of surface horizontal wind vectors between in circa 1850 and in circa 1985 a b c



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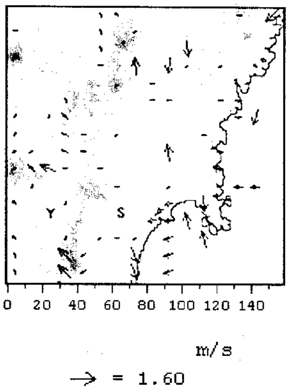
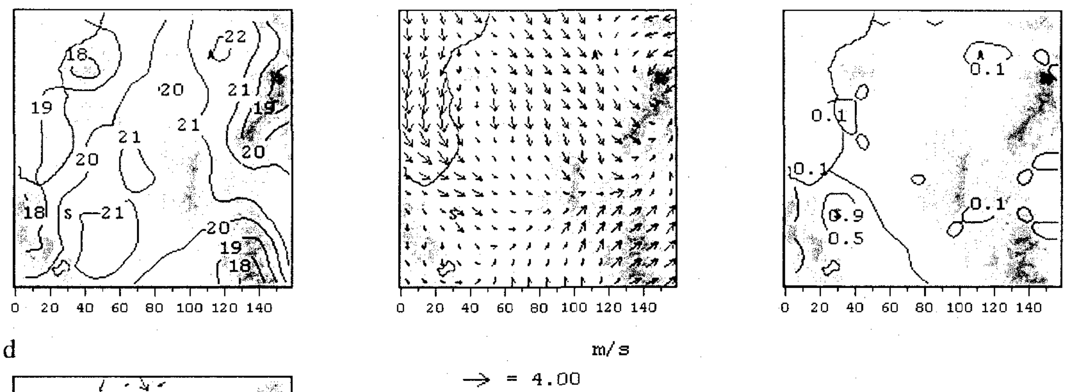


Figure 12 Computed results at 9PM in a calm and clear day in late July around Sendai
a. surface air temperature (℃)
b. surface horizontal wind system
c. difference of surface air temperature (℃) between in circa 1850 and in circa 1985
d. difference of surface horizontal wind vectors between in circa 1850 and in circa 1985

a b c



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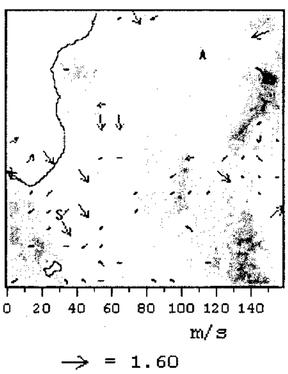

Figure 13 Computed results at 9PM in a calm and clear day in late July around Sapporo
a. surface air temperature (℃)
b. surface horizontal wind system
c. difference of surface air temperature (℃) between in circa 1850 and in circa 1985
d. difference of surface horizontal wind vectors between in circa 1850 and in circa 1985

6. Comparison with Observed Air Temperatures in Tokyo

Meteorological station's observations began in Tokyo (Otemachi) in 1876. Through comparison with those observed data the author examined the soundness of computed temperatures for c. 1850. The only data that were obtainable from 1876 to the present in the same format were the monthly averages for daily maximum and minimum temperatures. These data are not those for the calm and clear days targeted by this study; instead they include the influence of various synoptic conditions.

The author used the following procedure to process the original data in order to prepare data that could be compared with computed temperatures.

1) The author assumed that the differences between monthly averages containing the influences of various synoptic conditions and the data for a typical calm and clear day were the same for both stages. Another assumption was that both stages shared the same standard deviation. Unfortunately these assumptions have insufficient substantiation. These assumptions are in trouble if, in conjunction with advancing urbanization, there are major changes in the influence of land use on temperature on calm and clear days, or, putting it another way, changes in the influence on temperature by the disruption of wind systems. A further premise for these assumptions was that there was little difference in the frequencies of calm and clear days at the two stages.

2) In Otemachi, an observatory station of AMeDAS (Automated Meteorological Data Acquisition System) was settled in 1976 and these data (hourly) were available for analysis in the term around 1985. The daily maximum and minimum temperature averages and the standard deviations at Otemachi for July and August (since 1978 till 1997: 1,239 days as a whole) were 29.4±3.5°C (= AT_{max} in the below equations) and 23.5±2.7°C (= AT_{min} in the below equations), respectively. Values obtained by screening the data (234 days as a whole) from all 1,239 days for at least 10 hours of sunlight, 0 mm daily rainfall, and average daily wind velocity of under 6 m s^{-1} yielded a daily maximum temperature of 32.1±2.0°C (= AC_{max} in the below equations) and a daily minimum temperature of 24.9±2.3°C (= AC_{min} in the below equations). Finding only the differences in average values while ignoring variation in standard deviation yielded daily maximum and minimum differences of 2.7°C (= DA_{max} in the below equations; 32.1°C–29.4°C) and 1.4°C (= DA_{min} in the below equations; 24.9°C–23.5°C). The author considered these values to represent the differences between monthly averages containing the influences of various synoptic conditions and the data for a typical calm and clear day. In other words, the following equations were assumed available during the recent 135 years.

$$DA_{max\ (min)} = AC_{max\ (min)} - AT_{max\ (min)} \qquad (1)$$

$$EC_{max\ (min)} = MA_{max\ (min)} + DA_{max\ (min)} \qquad (2)$$

$AC_{max\ (min)}$: Average of daily maximum (minimum) temperature in typical calm and clear days (234 days as a whole in July and August since 1978 till 1997)
$AT_{max\ (min)}$: Average of daily maximum (minimum) temperature in total days containing the influences of various synoptic conditions (1,239 days as a whole in July and August since 1978 till 1997)
$MA_{max\ (min)}$: Monthly average of daily maximum (minimum) temperature (July and August)

$EC_{max\,(min)}$: Estimated daily maximum (minimum) temperature in typical calm and clear days (in late July)

3) The author averaged the July and August values from the monthly averages of daily maximum and minimum temperatures in Otemachi from 1876 to 1996 and investigated the long-term trends (Figure 14). Applying a linear function for diachronic change, the long-term trends for daily maximum temperature (3) and daily minimum temperature (4) were expressed as follows using y (number of the year with 1876 as 1) and T (°C).

$$T=0.0105y+28.9 \qquad (3)$$
$$T=0.0213y+21.0 \qquad (4)$$

T is equivalent to $MA_{max\,(min)}$ in *Eq.* (2). The correlation coefficients were 0.29 for daily maximum temperature and 0.66 for daily minimum temperature. On this basis the author estimated the temperature increases over the past approximately 135 years to be +1.5°C for daily maximum temperature and +2.8°C for daily minimum temperature.

The values for c. 1985 estimated on this basis were 30.1±3.5°C for daily maximum temperature and 23.3±2.7°C for daily minimum temperature. They are equivalent to $MA_{max\,(min)}$ in *Eq.* (2) for c. 1985. In consideration of the differences with the values for a typical calm and clear day, the values obtained for daily maximum and minimum temperatures on a calm and clear day in late July for c. 1985 were 32.8±2.0°C (=30.1°C+2.7°C) and 24.7±2.3°C (=23.3°C+1.4°C), respectively. They are equivalent to $EC_{max\,(min)}$ in *Eq.* (2) for c. 1985. As the computed values for c. 1985 were 33.2°C and 24.9°C, respectively, these figures were considered quite sound.

Similarly, the daily maximum and minimum temperature values for c. 1850 were 28.6±3.5°C and 20.5±2.7°C, respectively. They are equivalent to $MA_{max\,(min)}$ in *Eq.* (2) for c. 1850. Taking into account the differences with the values for a typical calm and clear day, the values obtained for daily maximum and minimum temperatures on a calm and clear day in late July for c. 1850 were 31.3±2.0°C (=28.6°C+2.7°C) and 21.9±2.3°C (=20.5°C+1.4°C), respectively. They are equivalent to $EC_{max\,(min)}$ in *Eq.* (2) for c. 1850. Computed values for c. 1850 were 31.6°C (0.3°C higher than EC_{max}) and 24.2°C (2.3°C higher than EC_{min}), with that for the daily minimum temperature being somewhat high.

One conceivable reason for this is that the author's study ignored the influence of climate change occurring over broader geographical areas than temperature increases that were caused by local land use changes. Maejima *et al.* (1980) claimed that regional cooling over the whole of East Asia during the 1950s canceled the effect of urbanization and induced a decline in the daily maximum temperature. Such wide-area's climate changes must be taken into account.

The author once again performed simulations for c. 1850 by assuming the effect of wide-area's climate change during the concerned period of time to be +2.0°C, and lowering by 2.0°C (K) the sea surface temperature, which was set at a constant value in the computings (Figure 15). The recomputed daily maximum and minimum temperatures were 29.8°C and 22.4°C, respectively, showing improvement (from 2.3°C higher to 0.5°C higher) in the result for daily minimum temperature. But as the result for daily maximum temperature was more than 1°C lower than the estimated value (EC_{max}), there is little possibility that the initial divergence was caused by ignoring climate change over a wider geographical area. The reason that the daily maximum and minimum temperatures rise at different rates over the 121 years, and that the difference is larger for daily minimum temperature, is conceivably the suppression of nighttime radiative cooling due to the development of the urban canopy structure (Kusaka *et al.*, 2001), which cannot be expressed by this model. It would doubtless be very worthwhile to perform the same kind of analysis on not only central Tokyo, but also on suburban locations where the urban canopy is not very developed.

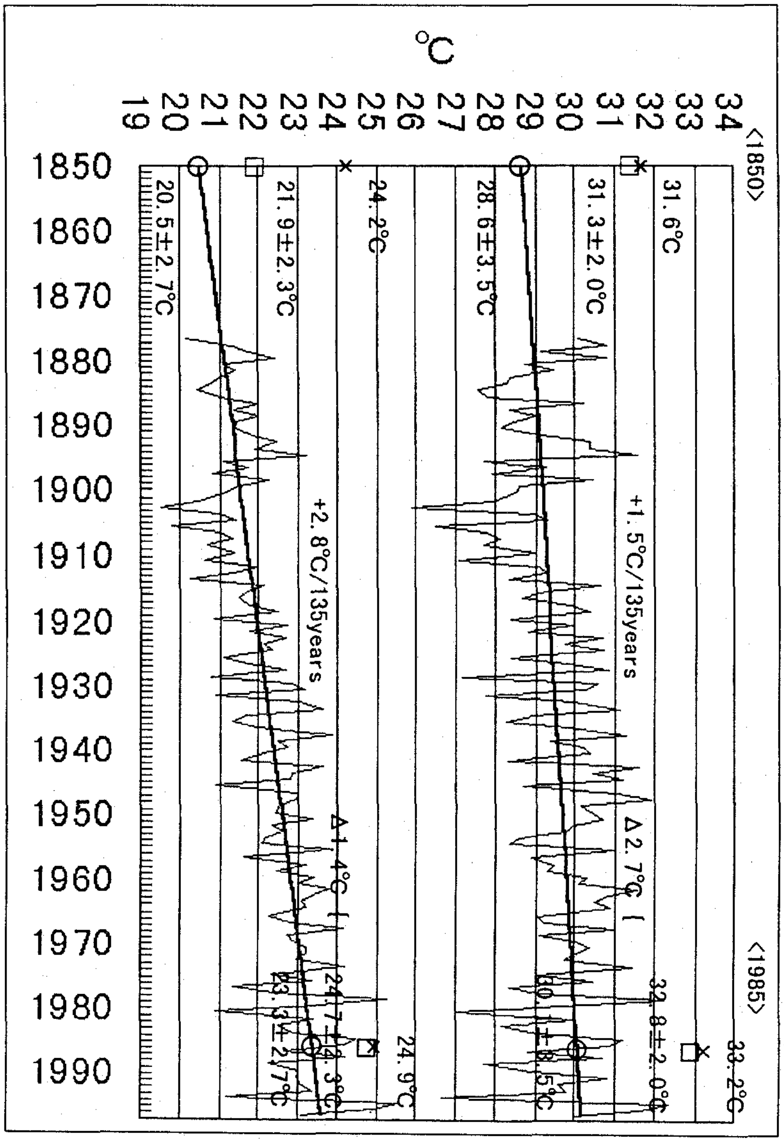

Figure 14 Daily maximum and minimum temperature (○) in Tokyo in 2 stages, estimated from the trend of 121 years

Estimated temperatures in a calm and clear day (□) and computed results (×) in late July were shown. Averages of monthly averages in July and August were used.

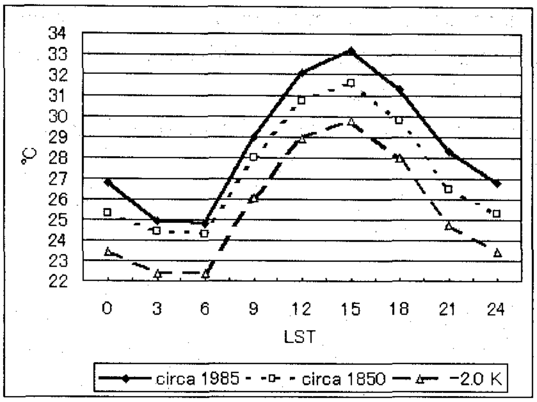

Figure 15 Comparison with a case of 2K decrease of sea surface temperature

7. Conclusions

By the numerical simulations with CSU-MM referring to LUIS, the author attempted to pick up the influence on surface air temperature around five big cities in Japan by regional warming related to land use change during recent 135 years. During four stages, the area showing the regional warming related to land use change has expanded. This feature was significant around Tokyo and Osaka. The maximum difference between c. 1850 and c. 1985 emerged at 9 PM and the minimum emerged at 6 AM. The former was 1.8°C in Tokyo (Otemachi).

Urbanization during four stages in these 135 years weakened the daytime penetration of sea breeze in the south Kanto Plain and it brought a regional warming. The warming area moved to north with expanding on the Kanto Plain by sea breeze since daytime to mid-night. But an effect of recovery of forest in the mountainous area in central Japan was not clear. In the Osaka Plain the movement of warming area by sea breeze was smaller than in the Kanto Plain.

Kusaka *et al.* (2000) has performed similar kind of computing around the Kanto Plain in c. 1985, c. 1950, and c. 1900. They gave results agreed well with this study but range of computed warming was slightly larger than the author's. They also figured out that the simulated sea breeze front in c. 1985 was more clearly defined around the northern end of the Tokyo metropolitan area. Such changes of wind system was given in this study too. But they did not show diurnal change of the computed factors, which the author showed.

The daily maximum and minimum temperature in c. 1850, estimated from observed data (monthly averages of daily maximum and minimum temperature) in Tokyo (Otemachi) since 1876, were compared with computed results. For this comparison, the method to estimate the daily maximum and minimum temperature in a calm and clear day in past was developed. In this method, the differences between the monthly averages, including the influences of many kinds of synoptic conditions, and the averages in calm and clear days, which were focused in this study, were regarded as common during four stages.

As a result of the comparison in c. 1850, computed daily maximum temperature agreed well with the estimated value. But computed daily minimum temperature was given higher than the estimated. This disagreement was not interpreted by the warming in the wider scale, due to a result of re-computing in the case of -2K of sea surface temperature decrease. This disagreement is related to the difference of annual warming rate between daily maximum and minimum temperature. This difference seems to come from the effect of urban canopy structure and its characteristic radiation environment. The mesoscale model used in this study could not express this effect.

The method in this study has a role to fill the temporal and spatial hole of historical climatology depending on the documents in the historical periods.

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References

Anthes R.A., Hsie E.-Y. and Kuo Y.-H. (1987): Description of the Penn State/NCAR Mesoscale Model Version 4 (MM4). NCAR, Boulder, USA.

Fujibe F. (1995): Temperature rising trends at Japanese cities during the last hundred years and their relationships with population, population increasing rates and daily temperature ranges. Pap. Meteor. Geophys., 46, p.35-55.

Fujino T., Asaeda T. and Wake A. (1994): The relation between heat island phenomena and geostrophic wind with an examle of Tokyo metropolitan area. Environmental Systems Research, 22, p.280-285. (in Japanese with English abstract)

Himiyama Y. (1995): Atlas. Asakura, Tokyo, Japan. (in Japanese)

Ichinose T., Shimodozono K. and Hanaki K. (1999): Impact of anthropogenic heat on urban climate in Tokyo. Atmospheric Environment, 33, p.3897-3909.

Jones P.D. (1988): Hemispheric surface air temperature variations: Recent trends and an update to 1987. J. Climate, 1, p.654-660.

Kessler R.C. and Douglas S.G. (1992): User's guide to the Systems Applications International Mesoscale Model (Ver. 2.0). Systems Applications International, California, USA.

Kimura F. and Takahashi S. (1991): The effects of land-use and anthropogenic heating on the surface temperature in the Tokyo metropolitan area: A numerical experiment. Atmospheric Environment, 25B, p.155-164.

Kondo H. (1990): A numerical experiment of the "extended sea breeze" in the Kanto Plain. J. Meteor. Soc. Japan, 68, p.419-434.

Kukla G., Gavin J. and Karl T.R. (1986): Urban warming. J. Climate. Appl. Meteor., 23, p.1265-1270.

Kusaka H., Kimura F., Hirakuchi H. and Mizutori M. (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, p.405-420.

Kusaka H., Kondo H., Kikegawa Y. and Kimura F. (2001): A simple single-layer urban canopy model for atmospheric models: Comparison with multi-layer and slab models. Bound. –Layer Meteor., 101, p.329-358.

Lenz J.-C. (1996): Energieumsetzungen an der Erdoberflaeche in Gegliedertem Gelaende. Zur Erlangung des akademischen Grades eines Doktors der Naturwissenschaften von der Fakultaet fuer Physik der Universitaet (TH) Karlsruhe genehmigte Dissertation. (in German)

Maejima I., Nogami M., Aoyama T., Oka S., Tagami Y., Hogetsu T., Sugihara Y., Yamashita S., Nishiyama Y. and Umemoto T. (1980): Recent climatic change and urban growth in Tokyo and its environs. Geographical Reports of Tokyo Metropolitan University, 14/15, p.27-48.

Mikami T. (1996): Summer climate variabilities of the Little Ice Age in Japan reconstructed from historical documents. Proceedings of the 1995 Nagoya IGBP-PAGES/REP-II Symp., Nagoya, Japan, p.8-13.

Ogasawara Y. (1990): An attempt to estimate the summer rainfall in Edo (old Tokyo) in the 1830s and 1840s. Geographical Review of Japan, 63A, p.593-605. (in Japanese with English abstract)

Park H.-S., Yasunari T., Yamane N. and Oda T. (1994): Detection of the urban climatic component based on the seasonal variations of surface air temperature anomaly. Geographical Review of Japan, 67A, p.561-574. (in Japanese with English abstract)

Pielke R.A. (1974): A three dimensional numerical model of the sea breezes over South Florida. Mon. Weather Rev., 102, p.115-134.

Ulrickson B.L. and Mass C.F. (1990): Numerical investigation of mesoscale circulations over the Los Angels basin. Part 1, A verification study. Mon. Weather Rev., 118, p.2138-2161.

Yamazoe Y. and Ichinose T. (1994): An analysis of urban heat islands in Tokyo and its environs – The comparison of cloudless nights with cloudy nights in autumn. Geographical Review of Japan, 67A, p.551-560. (in Japanese with English abstract)

Yoshikado H. (1994): Interaction of the sea breeze with urban heat island of different size and location. J. Meteor. Soc. Japan, 72, p.139-143.

Yoshino M. (1990/1991): Development of urban climatology and problems today. Energy and Buildings, 15/16, p.1-10.