Time-of-the-Day Dependence of Long-Term Temperature Changes at Urban Meteorological Stations in Japan

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Abstract

Long-term changes of urban temperature was examined by using hourly or four-hourly data at 42 stations in Japan. The magnitude of temperature change (T') was defined by the difference between averages for two periods: one from 1891 to 1928 and the other from 1977 to 1994. At many stations, T' values are larger at nighttime than in the daytime, and are nearly constant between a few hours after sunset and sunrise. Moreover, nighttime T' values are nearly equal to the change of daily minimum temperature ($T'_{\min}$). However, some stations in the northern part of Japan show larger values of $T'_{\min}$ than T' at each fixed time, with a difference of 1°C or more at stations in inland of Hokkaido. This indicates a decrease in nocturnal temperature fluctuation, and is likely to be explained by a weakening of the surface inversion due to urban growth.

1. Introduction

It is well known that the urban temperature anomaly is larger at nighttime than in the daytime (Landsberg, 1981; Oke, 1987). Accordingly, the long-term temperature trend in cities is characterized by a larger rise of daily minimum temperature than maximum temperature, although there is some possibility of global climatic change as another source of differential changes in minimum and maximum temperatures (Karl *et al.*, 1993; hereafter we omit “daily” for convenience, on the convention that “minimum and maximum temperatures” always indicate daily extremes). For Japanese cities, several researchers have detected such differences by using the database of the Japan Meteorological Agency (JMA) (Noguchi, 1994; JMA, 1994, 1996; Fujibe, 1995, 1997).

On the other hand, there is some uncertainty about detailed patterns of the diurnal variation of urban temperature. Most of previous studies on this subject have been based on urban-rural temperature difference (ΔT_{u-r}), which is found to be largest in the early evening at some cities but near sunrise at others (Landsberg, 1981; Oke, 1987; Sakakibara *et al.*, 1996). However, the evaluation of ΔT_{u-r} generally involves the possibility of bias arising from topographic influence, which can be a serious problem for many Japanese cities located in complex terrain.

In this respect, analysis of long-term changes based on hourly temperature data is expected to be informative as an alternative approach to the diurnal variation of urban temperature, but this approach has remained largely untapped due to the difficulty in collecting data, except for the recent few decades or a limited number of cities (Fujibe, 1994, 1996; Harada, 1982; Tso, 1996).

Another interesting problem is to examine whether and to what extent the trends of minimum and maximum temperatures are representative of nighttime and daytime temperature trends, respectively. Since minimum and maximum temperatures can be observed at any time of the day, their climatic averages and long-term trends should more or less differ from those of temperature at a fixed time of the day. Analysis of hourly data is expected to be useful in evaluating this difference.

The present paper describes the time-of-the-day dependence of long-term temperature changes at 42 stations in Japan in order to find the general features of diurnal variation of urban temperature. The analysis is based on hourly or four-hourly data collected from published tables. The results are compared with the changes of minimum and maximum temperatures in order to observe their difference from those of hourly temperatures.

Fig. 1. Location of cities and towns used for the analysis. The names of stations are shown by their first three letters except for Nagoya (Nago), Kumamoto (Kumm), Matsuyama (Maty), Nagano (Naga), Fukushima (Fuks), Fukui (Fuki), Matsumoto (Matm) and Kumagaya (Kumg). Hatching indicates an area of more than 1000 m above the mean sea level, and double hatching indicates that of more than 2000 m above the mean sea level.

2. Data and procedure of analysis

2.1 Data source

Up to the 1940's, meteorological observation in Japan was hourly at some stations and four-hourly (02, 06, 10, 14, 18, 22 JST) at most of the others, except for some stations with eight-hourly observations. For the period from 1891 to 1923, monthly statistics at each observation time are tabulated in "Annual Report of the Central Meteorological Observatory". Similar data are found in "Monthly Report of the Central Meteorological Observatory" for the period up to April 1929. The present study is based on these data for the 38 years from 1891 to 1928. This period will be denoted by "Period I" hereafter.

For the northern and central part of Japan (Hokkaido-Kinki districts), all the stations which entered into operation by the end of 1906 were used except for those with eight-hourly observation. For the western part of Japan (Chugoku, Shikoku,

Kyushu and Okinawa districts), analysis was limited to three stations (Kumamoto, Matsuyama and Tadoitsu, which provided hourly data and were likely to be unaffected by site changes) in order to save the labor of data input. The number of stations used for the analysis is 42, including 16 stations with hourly observation (Fig. 1, Table 1).

Since the middle of the 1970's, hourly data at meteorological stations have been stored on magnetic tapes of the JMA as part of the Automated Meteorological Data Acquisition System (AMeDAS). The present study is based on the data from 1977 to 1994. This period will be denoted by "Period II" hereafter.

Data of minimum and maximum temperatures were obtained from magnetic tapes compiled by the JMA in the same manner as Fujibe (1995, 1997).

Hereafter we denote the temperature at 01, 02, — JST by T_{01} , T_{02} , —, and minimum and maximum temperatures by $T_{\min}$ and $T_{\max}$, respectively.

Table 1. Stations used for the analysis.

Station	Pop. (10 ³) ¹⁾	Data period ²⁾	Hourly period
Tokyo	8163 ³⁾	1891	1891–1928
Yokohama	3221	1897	
Osaka	2624	1891	1891–1928
Nagoya ⁴⁾	2155	1891	1891–1928
Sapporo	1672	1891	1891–1928
Kobe	1477	1897	1897–1917
Kyoto	1461	1891	1910–1919
Kumamoto	579	1891	1891–1928
Hamamatsu	535	1891	
Niigata	486	1891	1915–1923
Matsuyama	443	1891	1891–1922
Kanazawa	443	1891	
Utsunomiya ⁴⁾	427	1891	
Gifu	410	1891	
Wakayama	397	1891	1891–1897
Asahikawa	359	1891	
Nagano	347	1891	
Hakodate ⁴⁾	307	1891	1891–1928
Akita	302	1891	
Aomori ⁴⁾	288	1891	
Maebashi	286	1897	1912–1925
Fukushima	278	1891	
Fukui ⁴⁾	253	1897	
Yamagata	249	1891	
Mito	235	1897	1906–1928
Matsumoto ⁴⁾	201	1898	
Kofu ⁴⁾	201	1895	
Fushiki	175	1891	
Obihiro	167	1894	
Tsu	157	1891	
Kumagaya	152	1897	
Ishinomaki	122	1891	
Hikone	100	1894	
Iida	92	1898	
Choshi ⁴⁾	85	1891	1912–1928
Takayama	65	1900	
Miyako	59	1891	
Abashiri	44	1891	
Nemuro	37	1891	1891–1924 ⁵⁾
Tadotsu	24	1892 ⁶⁾	1893–1925
Hachijojima	9	1906 ⁶⁾	
Suttsu	5	1891	

1) Population of the city or town in which the station is located (according to the census in 1990).

2) First year of the data period used in this study. The last year is 1928 for all the stations.

3) Population of the ward area.

4) Stations removed in the analysis of Fujibe (1995). See 2.2 for details.

5) Until March.

6) From July.

2.2 Calculation of the temperature difference between Periods I and II

The analysis is based on a procedure similar to that of Fujibe (1995, 1997). He used a least-squares method to calculate the long-term change rate in the time series of $T_{\min}$ and $T_{\max}$ at 60 stations in Japan. The time series were decomposed into (a) the long-term trends, (b) the year-to-year variation in the background temperature, (c) the discontinuities at site changes, and the residual term. The term (a) was expressed by a polynomial function. The term (b) was expressed by a combination of empirical orthogonal functions (EOFs) which were based on the departure of monthly mean temperature from its linear trend. The term (c) was expressed by a step function.

In the present analysis, the long-term change corresponding to (a) was expressed by a stepwise difference between Periods I and II instead of a polynomial function, because data for the period from 1929 to 1976 were lacking. For the same reason, the discontinuity at site changes was not evaluated. As for the background variation corresponding to (b), the EOF scores calculated by Fujibe (1995, 1997) were used as they were. Thus the least-squares criterion is

$$\sum_{m'=m-1}^{m+1} \left\{ \sum_{j=\text{Period I}} \left[T_h(j, m') - \overline{T}_h(m; \text{I}) - \sum_{n=1}^L b_{hn}(m) F_n(j, m') \right]^2 + \sum_{j=\text{Period II}} \left[T_h(j, m') - \overline{T}_h(m; \text{II}) - \sum_{n=1}^L b_{hn}(m) F_n(j, m') \right]^2 \right\} \rightarrow \text{Min.}, \quad (1)$$

where j is year, m is month, $T_h(j, m)$ is temperature at time h , and $\overline{T}_h(m)$ is a least-squares coefficient indicating the average for each period. The third term in each bracket is regarded as representing the interannual variation of the background temperature, with $F_n(j, m)$ as the score of the n -th EOF and $b_{hn}(m)$ as a least-squares coefficient. The number of the EOFs, L , was set to be 3 for the results shown in the following sections unless otherwise stated. The summation for three running months was used in order to smooth the month-to-month variation of the result. The temperature change between the Periods I and II is given by $\overline{T}_h(m; \text{II}) - \overline{T}_h(m; \text{I})$. This will be denoted by T'_h hereafter. The standard error in estimating T'_h is less than 0.2°C for most stations, and is negligible as far as the main features of T' are concerned.

Fig. 2. Schematic picture of the calculation of hourly $\bar{T}$ values at a station for which hourly data are available only for part of Period I. Hourly $\bar{T}$ values obtained by using the data of the hourly observation period are denoted by A's, four-hourly $\bar{T}$ values based on the data for the full period are shown by B's, and $D = A - B$. Circles indicate the corrected hourly values. See Subsection 2.2 for details.

There are some stations at which hourly data are available only for part of the Period I, with four-hourly observation for the remaining part (e.g., Kobe; see Table 1). For these stations, hourly $\bar{T}$ values can be inconsistent with four-hourly values because of the difference in data periods. Figure 2 illustrates the situation schematically. The values of $\bar{T}$ obtained for the hourly observation period (A) differ from those obtained for the full period (B) by $D = A - B$. In order to estimate hourly $\bar{T}$ values which should have been obtained if hourly data were available for the full period, D was interpolated to each hour by using cubic spline functions proposed by Akima (1970), and was added to the value of A.

The information on the effect of site changes was obtained from the analysis of Fujibe (1995). He applied several versions of the least-squares formulation, in which the effect of site changes was evaluated in some versions and not evaluated in others, and selected 46 stations where estimated trend was found to be insensitive to calculation conditions. We expect that T' values are also insensitive to site changes for these stations. They include 34 stations used in the present analysis other than those marked by 4) in Table 1. In the following analysis, we separate three stations (Sapporo, Asahikawa and Obihiro) where trends of minimum temperature were exceptionally large, and call the remaining 31 stations "selected stations".

It is to be noted that T' includes all the changes resulting from not only urban growth but also other

Fig. 3. Comparison of diurnal temperature variations averaged for 1891-1928 and 1977-1994 at Tokyo and Sapporo. The minimum and maximum temperatures are shown on the right of each graph.

causes. The contribution of natural and/or global changes will be discussed in 4.1. In addition, there can be a problem arising from changes in observational instruments. However, the instrumental bias is expected to be a fraction of a degree or less according to reports issued by the JMA (1965, 1974, 1984), while more detailed analysis is very difficult. Here we keep from entering into the observational problems on the reservation that they may not be totally denied.

3. Results

Figure 3 shows the diurnal variations of temperature ($\bar{T}$ calculated from Eq. (1)) in winter (December-February) and summer (June-August) at Tokyo and Sapporo as examples. At both stations, temperature is higher in Period I than in Period II. The difference between periods ($= T'$) is larger at nighttime than in the daytime. In particular, there is a large rise in the nighttime temperature in winter at Tokyo.

The minimum and maximum temperatures at Tokyo are nearly equal to the lowest and highest values of hourly temperatures, respectively, with differences of 1°C at most. However, the minimum temperature at Sapporo is substantially lower than hourly temperature at any time of the day. The difference is larger in winter than in summer, and in Period I than in Period II. For example, $\bar{T}_{06} - \bar{T}_{\min}$ is 3.1°C in winter in Period I, but is 1.9°C in Period II. This means that $T'_{\min}$ is larger than T' at a fixed time.

Figure 4 shows the seasonal and diurnal diagrams of T' at these cities. The temperature change is

Fig. 4. Season-time of the day section of T' for Tokyo and Sapporo. Contour intervals are 0.25°C . Dashed lines indicate the times of sunrise and sunset.

separated into daytime and nighttime régimes with a sharp transition in the morning and evening. It is interesting that the morning transition occurs after sunrise but the evening transition begins one or two hours before sunset.

In order to compare the features among cities and towns, the diurnal variations of T' at hourly observation stations are shown in Fig. 5 in the order of population. It can be observed that T' is larger in the nighttime than in the daytime for most stations and seasons, typically characterized by a rapid increase in the evening and a rapid decrease in the morning. More details of the results can be summarized as follows.

- (1) The value of T' at nighttime tends to be larger at larger cities, but there is not a perfect correlation between T' and the city size. For example, T' is relatively large at Kyoto and small at Kobe in spite of the nearly equal populations.
- (2) As for seasonal differences, T' at nighttime tends to be smaller in summer than in other seasons. However, this is not common to all the stations, and the large winter-summer difference at Tokyo is rather exceptional.

- (3) The day-night contrast of T' is relatively weak at Niigata (except in summer), Hakodate, Choshi, Nemuro and Tadotsu, and also Hamamatsu, Fushiki and Ishinomaki for which results are not shown. These stations are located in coastal areas, although some of them are likely to be influenced by site changes (Hakodate and Choshi) and some stations are in small cities or towns (Nemuro and Tadotsu).
- (4) The value of T' is nearly constant from just after sunset to sunrise with a change of only a fraction of a degree. However, some stations in the Kanto plain (Maebashi, Mito and Choshi) are characterized by largest T' values in the evening.
- (5) In spring and summer, T' has a weak maximum in midday at some cities (Osaka and Wakayama) and increases gradually in the afternoon at some others (typically Kyoto, Maebashi and Mito, as well as Sapporo and Kumamoto).
- (6) The values of $T'_{\min}$ and $T'_{\max}$ are nearly equal to T' at nighttime and midday, respectively. At Sapporo, however, $T'_{\min}$ is substantially larger than hourly values of T' with a difference of 1°C or more in winter. A weak but similar feature is also observed at Kyoto.

Among these results, the features described in (1) and (2) roughly agree with previous findings based on minimum and maximum temperatures (Noguchi, 1994; Fujibe, 1995). The feature in (3) corresponds to the small rise rates of $T_{\min}$ at coastal stations (Fujibe, 1995). The features (4)–(6), together with that observed in Fig. 4, are our new findings which cannot be detected without hourly data.

As a different presentation of the result, Fig. 6 shows the annual variation of T' at four-hourly observation times and daily extremes for Tokyo, Sapporo and Obihiro, as well as the average over the 31 selected stations. Obihiro is unique for the large values of T' in winter in spite of the small population, and also for the increase of T' during the nighttime in winter ($T'_{18} < T'_{22} < T'_{02}$) with $T'_{\min}$ still larger by about 1°C . A similar feature is found also at Asahikawa (not shown). Other stations are generally characterized by smaller change of T' during the night. On the average for the 31 selected stations, T' is almost constant during the nighttime with only a small difference from $T'_{\min}$.

In order to examine the generality of the diurnal T' patterns described so far, some statistical relations are presented below. The values of correlation coefficients and ratios presented here are based on the results obtained for the 31 selected stations with $L = 3$ in Eq. (1). In addition, the results obtained

Fig. 5. Diurnal variation of the magnitude of temperature rise (T') at hourly observation stations. The magnitudes of rise in minimum and maximum temperatures ($T'_{\min}$ and $T'_{\max}$) are shown on the right of each graph.

for all the stations with $L = 0$ are shown in parentheses as a measure of their sensitivity to the method of evaluating T' .

Figure 7a is a scatter diagram of T'_{06} and T'_{18} in winter representing the values after sunset and before sunrise, respectively. The two parameters are nearly in a one-to-one relationship, with a correlation coefficient of 0.91 (0.91). The ratio of the averages of T'_{18} and T'_{06} among the stations, hereafter denoted by $T'_{18} \div T'_{06}$, is 1.09 (1.05). This reflects the approximate constancy of T' during the nighttime. However, T'_{06} is larger than T'_{18} at some stations such as Obihiro, Kyoto and Asahikawa, where temperature changes are comparatively large. The opposite feature ($T'_{18} > T'_{06}$) is found at some stations in the Kanto plain (e.g., Maebashi and Mito).

Figure 7b shows the relationship between T'_{06} and $T'_{\min}$. Again, there is a high correlation between the two parameters with a coefficient of 0.96 (0.95). The ratio $T'_{\min} \div T'_{06}$ is 1.18 (1.22), which means that $T'_{\min}$ is slightly larger than T'_{06} , on the average. In particular, $T'_{\min}$ is substantially larger than T'_{06} at stations in the northern part of Japan (Obihiro,

Fig. 6. Annual variation of T' at four-hourly observation times and for minimum/maximum temperature.

Fig. 7. Scatter diagrams of specified parameters for winter (December–February). Circles drawn in solid lines indicate “standard” stations and Sapporo, Asahikawa and Obihiro, and those drawn in dashed lines indicate other stations. The area of each circle is proportional to the fourth root of the population of the city or town in which the station lies. Thin dotted lines in the left and the center diagrams indicate the $y = x$ relation, and the dashed line in the right diagram shows the result of linear regression.

Fig. 8. Same as Fig. 7, but for summer (June–August).

Sapporo and Asahikawa, and also Akita and Yamagata). A similar relationship is obtained for T' at other time of the night.

As seen in Fig. 3, Sapporo is characterized by a large difference between not only T'_{min} and T' and $\overline{T}_{min}$ and $\overline{T}$ at a fixed time. In order to examine whether this is a general feature, the relationship of $\overline{T}_{06} - \overline{T}_{min}$ and $T'_{06} - T'_{min}$ is shown in Fig. 7c. Here $\overline{T}$ in Period I is used because it is closer to the value unaffected by urban effects than that in Period II. We can find a negative correlation between the two parameters with a correlation coefficient of -0.55 (-0.81). The absolute values of $\overline{T}_{06} - \overline{T}_{min}$ and $T'_{06} - T'_{min}$ are largest at some stations in the northern part of Japan, while they are relatively small at large cities in Honshu, such as Tokyo, Yokohama and Osaka. The minimum-fixed time temperature difference can be regarded as a reflection of temporal fluctuation of nighttime temperature, while the

relationship in Fig. 7c indicates its long-term decrease with a higher rate at stations where it used to be larger. More discussion of this feature will be presented in Subsection 4.3.

Figure 8 shows the diagrams for summer. Here T'_{22} and T'_{02} are used as nighttime T' values because sunset and sunrise are around 19 JST and 04 JST, respectively. The relationship between T'_{22} and T'_{02} (Fig. 8a) is almost one-to-one, with a correlation coefficient of 0.97 (0.97) and a ratio of $T'_{22} \div T'_{02} = 1.04$ (1.01). There is also a nearly one-to-one relationship between T'_{02} and T'_{min} (Fig. 8b) with a correlation coefficient of 0.94 (0.94) and a ratio of $T'_{min} \div T'_{02} = 1.04$ (1.03). In other words, the minimum-fixed time difference of T' is smaller in summer than in winter. Nevertheless, there is a high negative correlation between $\overline{T}_{02} - \overline{T}_{min}$ and $T'_{02} - T'_{min}$ (Fig. 8c) with a correlation coefficient of -0.78 (-0.76).

4. Discussion

4.1 On the temperature changes due to non-urban effects

Separation of urban and non-urban components in long-term temperature changes has been a controversial problem both in studies of the global climate and the urban climate (Portman, 1993; Hughes and Balling, 1996; Kato, 1996). Previous studies for Japanese cities have mostly used the data at rural sites as a source of non-urban trends (Noguchi, 1994; Kato, 1996), although rawinsonde data are available for the recent few decades as another source of reference temperature (Fujibe, 1994, 1996). The estimation of non-urban trends from rural data is based on two assumptions. One is that the urban effect is totally absent at rural sites, and the other is that non-urban changes are spatially homogeneous or coherent. However, many "rural" stations in Japan are in fact located at cities or towns with a population of more than ten thousand, so that the effect of urbanization cannot be denied completely. Moreover, most of these stations are located at coasts exposed to the ocean, while many cities are located in plains or basins, so that differential temperature changes between urban and rural stations may arise from heterogeneous response to sea surface temperature and/or radiational forcing. For these reasons, it is very difficult to evaluate urban warming accurately.

The magnitude of estimated non-urban trends in Japan differs according to researchers and data periods. For the latter half of the 20th century, negative temperature trends are found in some seasons (Noguchi, 1994). The cooling trend in summer seems to be related to the falling trend of the sea surface temperature (Fujibe, 1996). On the other hand, Kato (1996) analyzed the temperature for 1920–1992 and estimated the natural rising rate to be $0.8^{\circ}\text{C}/(100 \text{ years})$ on the annual average over Japan. This roughly agrees with the report of the JMA (1994), which shows that the average trend at 15 stations in Japan for 1898–1992 is $0.9^{\circ}\text{C}/(100 \text{ years})$. However, some of these stations are located at cities with a population of over 100000, and the report admits that "there exists a major problem in distinguishing the climate due to the increase of greenhouse gases from the change in temperature due to urbanization ...". On the other hand, analysis of a hundred years' data at five stations in small cities and towns yields a trend of $0.5\text{--}1^{\circ}\text{C}$ for the minimum temperature and $0\text{--}0.5^{\circ}\text{C}$ for the maximum temperature (Fujibe, 1995). These are close to the global average trend (*e.g.*, Karl *et al.*, 1993), although there is no guarantee that they are an accurate estimation of non-urban temperature change.

In this situation, we should admit the possibility of some contamination from non-urban effects in our results. However, non-urban changes are likely to be

Fig. 9. Potential temperature profiles at Tsukuba averaged for winter months (January, February and December) in 1992 and 1993.

of minor contribution at large cities where T' is well above 1°C , and the diurnal pattern of T' at these cities can be regarded as representing the time-of-the-day dependence of urban warming.

4.2 Constancy of T' during the nighttime

The approximate constancy of T' during the nighttime is one of the main findings in this study. Here we discuss whether the constancy of T' means the steady state of the urban heat island.

Previous studies for urban-rural temperature difference (ΔT_{u-r}) have given more complicated diurnal patterns. For example, the seasonal-diurnal diagram of ΔT_{u-r} for Chicago (Ackerman, 1985) indicates that ΔT_{u-r} is nearly constant during the night in winter but is largest in the evening in summer. Yamazoe and Ichinose (1994) show that ΔT_{u-r} for Tokyo in autumn is nearly constant during the night under fair weather, but is largest before midnight under cloudy weather. These results suggest that ΔT_{u-r} can be temporally variable according to seasons and/or weather conditions.

Some statistical studies show that ΔT_{u-r} is negatively correlated with the intensity of surface inversion (Landsberg, 1981; Lee, 1975). This implies that the temporal change of the urban temperature anomaly depends on that of inversion intensity. As climatic data of the low-level temperature profile, Fig. 9 shows the vertical distribution of potential temperature in winter at Tsukuba (60 km northeast of Tokyo), which has been slightly urbanized but can be still regarded as representing the rural area of the Kanto plain fairly well. Data were taken from monthly statistics of observation at the 213 m tower of the Meteorological Research Institute (1995), and potential temperature was calculated by $T + \Gamma_d z$, where Γ_d is the dry adiabatic lapse rate (9.8 K/km) and z is height above the ground. One can see that the inversion intensifies with time during the night; the potential temperature difference within the lowest 200 m increases from 2.4°C at 18 JST to 4.1°C at 06 JST. The unsteadiness of the inversion intensity

Fig. 10. Hourly temperature records on all the days in January 1994. Circles indicate the lowest hourly temperatures between midnights.

again suggests that the temporal change of urban heat-island intensity is dependent on a delicate heat balance of the surface layer.

Kimura and Takahashi (1991) examined the urban effects in and around Tokyo by using a numerical model. Their result shows that the temperature anomaly at Tokyo, compared with the case in which the urban effects were eliminated, increases during the night if the effect of anthropogenic heat is solely incorporated, but is more nearly constant if the effect of surface properties is combined. This also implies a complicated mechanism for the time variation of urban temperature anomaly.

As described here, we can find no evidence to support the steady state of the urban heat island during the nighttime. In other words, a physical explanation for the constancy of T' is not straightforward. We desist here from further inquiry into this matter and leave it for future studies.

4.3 Minimum-fixed time difference of temperature changes

Another finding in this study is a differential change between the minimum temperature and the temperature at a fixed time of the night. This difference, represented by $T'_{06}-T'_{\min}$ or $T'_{02}-T'_{\min}$ in Figs. 7c and 8c, is negatively correlated with the difference between minimum and fixed time temperature ($T_{06}-T_{\min}$ or $T_{02}-T_{\min}$). In particular,

Table 2. Statistics of nighttime temperature variations ($^{\circ}\text{C}$) as explained in Section 4.3.

	Sap	Shin	Obi	Mem	Tok	Shim
$T_{06}-T_a$	0.52	0.80	0.67	0.93	0.35	0.50
T_a-T_b	0.47	0.88	0.38	0.80	0.12	0.19
T_b-T_c	0.66	1.09	0.72	1.18	0.24	0.36
Subtotal ($T_{06}-T_c$)	1.65	2.78	1.77	2.91	0.72	1.05
$T_c-T_{\min}$	0.27		0.27		0.20	

Full names of stations: Sapporo, Shinshinotsu, Obihiro, Memuro, Tokyo, Shimotsuma

some stations in the inland of Hokkaido (Sapporo, Asahikawa and Obihiro) is characterized by $|T'_{06}-T'_{\min}|$ exceeding 1°C in winter with a $T_{06}-T_{\min}$ of about 3°C . Here, we examine the meaning of this result by comparing the nocturnal temperature variations at urban and rural stations.

Figure 10 shows the time series of hourly temperature at four AMeDAS stations in Hokkaido for all the 31 days in January 1994. The two rural stations, Shinshinotsu and Memuro, are located on flat terrain 30 km northeast of Sapporo and 20 km west of Obihiro, respectively. One can see that the nighttime temperature at the rural sites is not only lower on the monthly average but also more variable with time than at the cities. Moreover, a strong cooling in a single night can generate two minimum temperatures before and after midnight, namely in the late evening of a day and in the early morning of the next day. Thus the difference between the minimum temperature and the temperature at a fixed time results from not only the temperature fluctuation within a night but also from the night-to-night variation.

For the sake of quantitative comparison, differences between the following quantities are listed in Table 2 on the average for the winter months (January, February and December) from 1977 to 1994:

- T_{06} : Temperature at 06 JST
- T_a : Lowest hourly temperature between 05 and 07 JST
- T_b : Lowest hourly temperature between 21 JST on the previous day and 09 JST on the day
- T_c : Lowest hourly temperature between 00 and 24 JST
- $T_{\min}$: Daily minimum temperature based on continuous observation from 00 to 24 JST

The differences among T_{06} , T_a and T_b result from within-night variation, while the difference between T_b and T_c results mainly from night-to-night variation. The difference between T_c and $T_{\min}$ corresponds to variation on a time scale of less than

one hour. It can be found from Table 2 that both within-night variation and night-to-night variation are larger at the rural sites than at the cities by several tens of percent, so that $T_{06}-T_c$ is nearly 3°C at the rural stations (and also at many other rural stations in the inland of Hokkaido). This is close to $\overline{T_{06}-T_{\min}}$ at Sapporo and Obihiro in Period I.

Table 2 also shows the statistics for Tokyo and Shimotsuma, which is at a rural site 60 km north of Tokyo. In comparison to stations in Hokkaido, $T_{06}-T_{\min}$ (or $T_{06}-T_c$) is small at these stations, especially at Tokyo. Even in Hokkaido, $T_{02}-T_{\min}$ is much smaller in summer than $T_{06}-T_{\min}$ in winter, as may be seen from the comparison of Figs. 7c and 8c. In other words, the large variation of nocturnal temperature is a typical feature of the northern part of Japan in winter.

Some observational studies show a large temperature fluctuation corresponding to intermittent breakdown of surface inversion due to external forcing and/or internal gravity waves (e.g., Nappo, 1991; Parker and Sethu Raman, 1993). A strong nocturnal inversion has been found to develop inland of Hokkaido in winter as a result of radiational cooling over a snow-covered surface with low vapor density in the air (Nakamura and Magono, 1982). On the other hand, the temperature fluctuation associated with a surface inversion is likely to be weak at urban sites, where a strong inversion does not develop. We can therefore consider that the long-term decrease of nighttime temperature variability has resulted from a weakening of surface inversion due to urbanization.

4.4 On the daytime temperature change

While we have mainly paid attention to the nighttime features, our results also indicate a weak signal of urban temperature anomaly in midday and early afternoon of spring and summer, as described in (5) in Section 3. The gradual increase of T' in the early afternoon is similar to the behavior of ΔT_{u-r} for a city in the Kanto plain (Sakakibara *et al.*, 1996). It is possible to interpret these features as a reflection of the sensible heat surplus over the city, where reduced evapotranspiration can result in extra heating of a few hundred watts per square meter on a sunny day of spring and summer (e.g., Oke, 1987). For the Tokyo metropolitan area, this heat surplus has been detected statistically as a pressure anomaly (Fujibe, 1987, 1994).

However, urban trends in daytime temperature are not large enough to be free from contamination by non-urban factors such as the effect of sea surface temperature (Fujibe, 1996). In this respect, we cannot take our result as conclusive but only a suggestion for future studies.

5. Summary

(1) The magnitude of temperature change (T') between Period I (1891–1928) and Period II (1977–1994) is nearly constant during the night. However, T' is largest in the evening at some cities in the Kanto plain. On the other hand, T' is largest in the morning at Obihiro and Asahikawa, where T' values are exceptionally large.

(2) The T' values in the nighttime are nearly equal to $T'_{\min}$, namely the rise of daily minimum temperature. However, some stations in the northern part of Japan are characterized by a larger change of daily minimum temperature than that at a fixed time, with a difference of 1°C or more at stations in the inland of Hokkaido. This corresponds to a decrease in nocturnal temperature fluctuation, presumably resulting from a weakening of surface inversion due to urban growth.

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都市気象官署における気温の経年変化量の時刻依存性

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北海道～近畿地方を中心とする気象官署 42 地点を対象にして 1891～1928 年の時刻別気温の資料（月別値）を収集し、これを 1977～1994 年のアメダス資料と比べることにより、都市における長期的な気温上昇量の時刻依存性を調べた。気温上昇量は多くの都市で昼間よりも夜間に大きく、日没直後や明け方までは一定であった。また、夜間の気温上昇量は日最低気温の上昇量とほぼ等しかった。ただし、冬の北日本では日最低気温の上昇量が時刻別気温の上昇量を上回る傾向があり、北海道の内陸都市（札幌・旭川・帯広）では両者の間に 1°C かそれ以上の差が認められた。これは夜間気温の時間変動幅が減少したことを反映しており、その理由として都市化による接地逆転の弱化が考えられる。