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Review

Urban warming in Japanese cities and its relation to climate change monitoring

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ABSTRACT: This article briefly reviews urban warming studies in Japan, where many of the stations established by the beginning of the 20th century are located in cities that have undergone rapid industrialization. The recorded rate of temperature increase is a few degrees per century in large cities and tends to be larger at night than during the daytime. In some cities, the increase in annual extreme minimum temperature exceeds 10 °C century^{-1}. On the other hand, recent numerical studies have revealed widespread urban warming around Tokyo and other megacities during afternoons of the warm season as a result of extensive urbanization that enhances daytime surface heating. An analysis using data from the dense Automated Meteorological Data Acquisition System network has shown that an urban bias in recent temperature trends is detectable not only in densely inhabited areas but also at slightly urbanized sites with 100–300 people km^{-2}, indicating the need for careful assessment of the background climate change. There is also some evidence of microscale effects on observed temperature, as revealed by an analysis of the relationship between trends in temperature and wind speed. Copyright © 2010 Royal Meteorological Society

KEY WORDS urban warming; urban temperature; urban heat island; temperature trend; Japan

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1. Introduction

With the rapid development of cities in Japan, there has been growing interest in urban warming. Twelve Japanese cities have a population of more than 1 million (Figure 1). Large metropolitan areas are referred to as *heat islands* because they are hotter than surrounding rural areas, which aggravate the summer heat discomfort that people feel. In 2004, the Inter-Ministry Coordination Committee of the Japan Government adopted the 'Outline of the Policy Framework to Reduce Urban Heat Island Effects' (http://www.env.go.jp/en/air/heat/heatisland.pdf) to advance cooperative actions for mitigating heat islands in large urban areas. The Japan Meteorological Agency (JMA) has issued a 'Heat Island Monitoring Report' every year since 2004 (http://www.data.kishou.go.jp/climate/cpdinfo/himr/index.html, in Japanese); these technical articles on urban climate changes report the results of climatological analyses and numerical simulations.

In the context of global climate change, urban warming can bias results obtained for background monitoring, as many of the observatories that have been in operation for a long time are located in cities (Karl *et al*., 1988; Jones *et al*., 1990). Some research has suggested that the globally averaged temperature trend is hardly affected by urbanization (Jones *et al*., 1990; IPCC, 2007), and many studies have emphasized the smallness of the urban contribution to recent temperature data (Peterson *et al*., 1999; Peterson, 2003; Li *et al*., 2004; Pepin and Seidel, 2005; Peterson and Owen, 2005; Parker, 2006, 2010). In some regions, however, urban warming has been found to have contributed substantially to observed temperature changes at stations located in cities (Hansen *et al*., 2001; DeGaetano and Allen, 2002; Kim and Baik, 2002; Choi *et al*., 2003; Zhou *et al*., 2004; Griffiths *et al*., 2005; Lim *et al*., 2005; Hale *et al*., 2006; Hua *et al*., 2008; Jones *et al*., 2008; Ren *et al*., 2008; Kataoka *et al*., 2009; Lai and Cheng, 2010). Changes in microscale environments can also affect observed temperature (Parker, 1994; Hawkins *et al*., 2004; Changnon and Kunkel, 2006; Mahmood *et al*., 2006; Runnalls and Oke, 2006; Pielke *et al*., 2007).

This article is a brief review of urban climate studies in Japan, with a focus on long-term warming. Section 2 gives the outline of traditional urban climatology, which has focused on nocturnal heat islands. Section 3 describes some features of warm-season daytime 'extended heat islands'. The next two sections summarize recent works on temperature changes related to local environments as factors affecting climate monitoring. Section 4 reviews an analysis of the urban contribution to temperature trends, including those at stations in small cities and towns (Fujibe, 2009b), in light of updated data. Section 5 gives

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a brief discussion of microscale effects on observed temperature changes on the basis of an analysis of Fujibe (2009a).

Kanda (2007) reviewed physical studies of urban atmospheric processes, and Kusaka (2008) reviewed recent developments in urban climatology in Japan, especially numerical studies of extended heat islands and their dynamic effects on wind and precipitation.

2. An outline of urban warming in Japan

The population of Japan has increased to nearly four times than that in the mid-19th century, whereas the growth rate has been even higher in several large cities. Figures 2 and 3 show the population distribution around Tokyo and Osaka, respectively. At present, the population of Tokyo Metropolis, which includes the 621 km^2 ward area (formerly Tokyo City) and its western suburbs, is about ten times that in the 1880s (Figure 4). For the past few decades, the population of Tokyo Metropolis has become almost saturated, while the surrounding prefectures have rapidly developed along with the expansion of the urban area. The areas around Osaka and Nagoya are also extensively urbanized. According to the 2005 census, the total population within 50 km of Tokyo, Osaka and Nagoya is 30.6, 16.5 and 8.8 million, respectively.

The relative warmth of some large cities in Europe, in comparison with surrounding areas, was already recognized in the 19th century (Yoshino, 1975; Landsberg, 1981). In Japan, early studies of urban climates were performed in the 1930s, corresponding to the period of urban growth before World War II (Sasakura, 1931; Arakawa, 1938; Fukui and Wada, 1941; Figure 5). These studies continued in the post-war period, when strong economic growth and industrial development were causing serious environmental problems and increasing the interest in urban climates. Some of the findings of these studies have been published in English or in articles with an English abstract for large cities (Kawamura, 1985; Fujibe, 1987, 1988b; Yamazoe and Ichinose, 1994; Yamashita, 1996; Sugawara *et al.*, 2004), medium-sized cities (Kawamura,

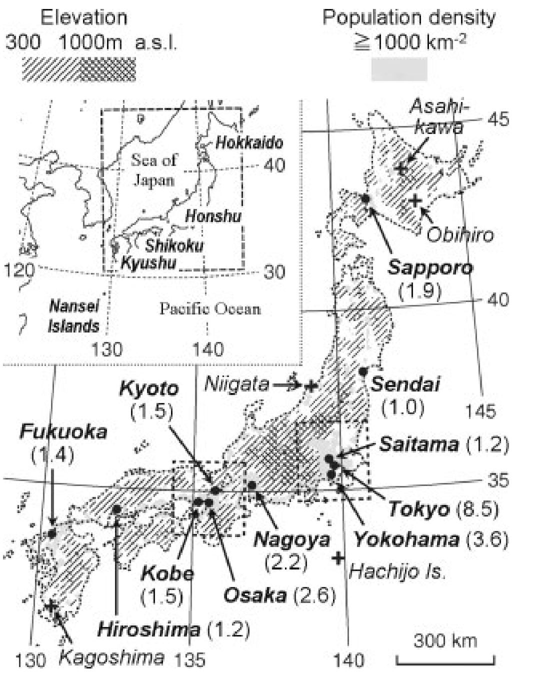

Figure 1. Topography of mainland Japan (details of the boxed area in the upper left). Dots indicate cities having a population ($\times 10^6$, shown in parentheses) of more than 1 million according to the 2005 census. In addition, Kawasaki City (1.3 million) is between Tokyo and Yokohama. Crosses indicate other stations that appear in the text.

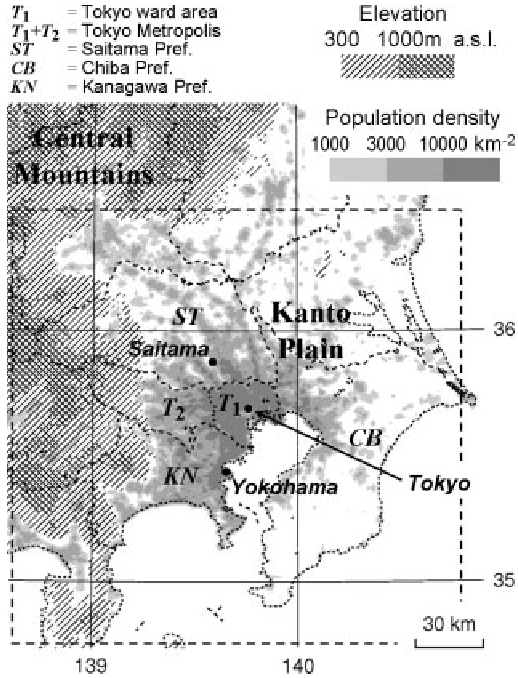

Figure 2. Topography and population density of the region around Tokyo. Dashed lines indicate the area shown in Figure 10.

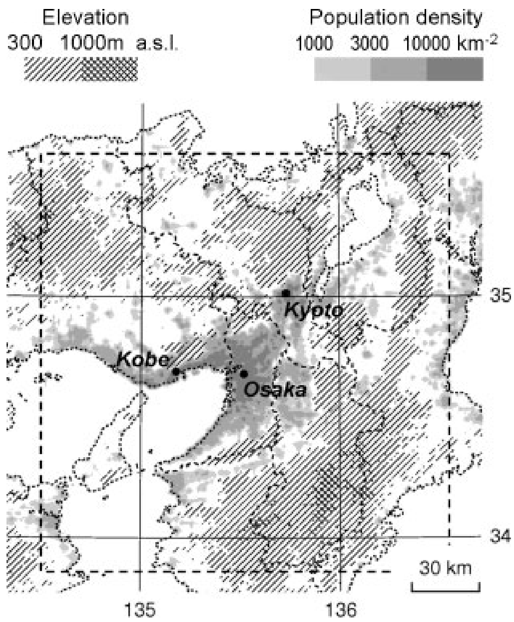

Figure 3. Topography and population density of the region around Osaka. Dashed lines indicate the area shown in Figure 12.

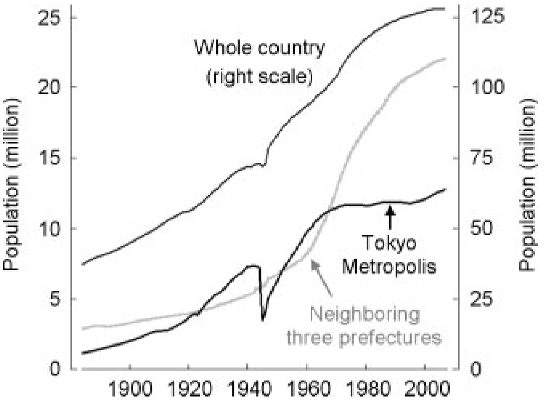

Figure 4. Long-term changes of population of Tokyo Metropolis and the three neighbouring prefectures (Saitama, Chiba and Kanagawa), as well as population changes in the whole country of Japan.

1964; Yamashita *et al*., 1986; Sakakibara and Itoh, 1998; Sakakibara *et al*., 1998; Sakakibara and Owa, 2005), small towns and settlements (Tamiya, 1968; Tamiya and Ohyama, 1981; Sakakibara and Morita, 2002) and cities of various sizes (Yoshino, 1975; Park, 1987; Fujibe, 1988a, 2010; Sakakibara and Kitahara, 2003; Sakakibara and Matsui, 2005).

Like many regions of the world (Landsberg, 1981; Oke, 1987), heat islands in Japanese cities are more conspicuous at night than during the daytime, corresponding to the low mixing depth in the stable nocturnal surface layer. In particular, intense heat islands tend to develop during the cold season when there is a strong nocturnal inversion in rural areas, apart from regional differences that are dependent on topography and prevailing weather conditions. Studies have also shown that urban parks tend to be cooler than surrounding business areas (Hamada and Mikami, 1994; Narita *et al*., 2004; Sugawara *et al*., 2006; Nagatani *et al*., 2008).

Long-term temperature records from urban stations in Japan indicate that substantial warming has occurred (Fukui, 1957, 1968, 1969; Omoto and Hamotani, 1979, 1980; Yoshino, 1981; Park *et al*., 1994; Fujibe, 1995, 1997, 2009b; Kato, 1996; Yamashita *et al*., 1997; Ichinose, 2003; Hajima *et al*., 2004; Kataoka *et al*., 2009). Figure 6 shows the departure of the annual mean temperature (T_{mean}) from the average during 1901–1920 at Tokyo and Hachijo Island, which is 300 km south of Tokyo, together with the average of the 17 stations that are used by JMA for monitoring climate change across Japan (for their locations, see JMA, 2009). The linear increasing trend of T_{mean} at Tokyo was 3.00 °C century^{-1} from 1901 to 2008, which is much higher than that at Hachijo Island (0.56 °C century^{-1}) or the 17-station average (1.14 °C century^{-1}). The trend of sea surface temperature near the east and west coasts of Japan was 1.0–1.3 °C century^{-1} from 1901 to 2008 according to JMA (2009, Figure 2.2.1), although there is a possibility of instrumental bias in the mid-20th century (Thompson *et al*., 2008). The rate of increase of the daily minimum temperature T_{min} at Tokyo (3.88 °C century^{-1}) was larger than that of the daily maximum temperature T_{max} (1.78 °C century^{-1}), so the daily range has decreased. In its rapid urban warming, Japan may differ from Europe and North America, where a recent temperature increase in cities is not conspicuous in spite of the existence of heat islands (Jones *et al*., 2008; Parker, 2010). A possible explanation for this difference is the rapid growth of Japanese cities, as well as the fact that many urban meteorological stations in Japan are located in or near business areas rather than in parks, as in some other countries. For example, the observation site in Tokyo is adjacent to the main building of the JMA in the central part of the city (Figure 7), although it is near the Imperial Palace grounds, which are largely covered with vegetation.

Rapid increases of temperature, especially of T_{min}, have been observed in other large Japanese cities as well (Fujibe, 1995, 1997; Table I). Figure 8 shows the relationship between the temperature trend and the city population according to the 1990 census (P_{90}). Both the T_{min} trend and P_{90} ($r = 0.60$), and the T_{max} trend and P_{90} ($r = 0.38$) are positively correlated. The correlation

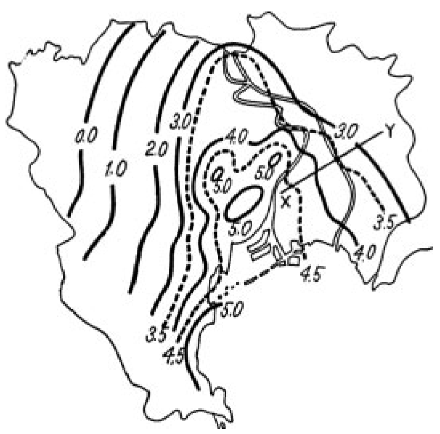

Figure 5. Temperature distribution (°C) in Tokyo City (currently the ward area) observed using vehicles starting at 2330 Japan Standard Time (JST), 6 March 1939 (Fukui and Wada, 1941).

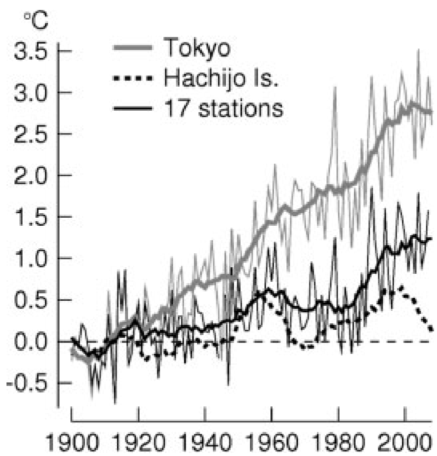

Figure 6. Time series of the departure of annual mean temperature from the average for 1901–1920 at Tokyo and Hachijo Island, and from the average of 17 stations across Japan. Thin and thick lines indicate annual values and the 11-year running average, respectively.

Figure 7. The observation station of Tokyo viewed from the main building of the JMA. The dotted circle indicates the position of the thermometer.

coefficients increase to 0.72 and 0.52, respectively, if stations that have some data uncertainty due to site changes and the three Hokkaido stations that have exceptionally large T_{min} trends, as detailed in the next paragraph, are omitted. The large scatter among stations, however, implies not only variability of urban signals among stations but also that non-urban factors affect the temperature changes.

The three stations in Hokkaido (Sapporo, Asahikawa and Obihiro) showed an exceptionally rapid increase of T_{min} in winter. Figure 9 shows the time series of annual extreme minimum temperature (A_{min}) at Tokyo and these three stations. The trend of A_{min} at an urban site is generally higher than that of T_{min}, because A_{min} typically corresponds to strong nocturnal cooling under clear skies and low wind speed, which are the conditions for an intense heat island. The trend of A_{min} at Tokyo, 6.2 °C century^{-1}, is about 1.6 times that of T_{min}. At Sapporo, Asahikawa and Obihiro, the A_{min} trend exceeds 10 °C century^{-1} (i.e. 10.6, 10.9 and 12.0 °C century^{-1}, respectively). These strong trends in extreme minimum temperature in Hokkaido can be partly explained by the wintertime snow cover, which is accompanied by a strong nocturnal inversion that favours the formation of large urban–rural temperature differences at night, as well as snow removal and melting in cities, which reduce the nighttime cooling. Another possible cause of the strong trends is the rapid growth of these cities. In 1900, Sapporo was a city of only 46 000 people (80 000 people if the area

Table I. Linear temperature trends (1931–2008, °C century^{-1}) in large cities in Japan.[a].

	Population in 2005 ($\times 10^3$)	T'_{mean}			T'_{max}	T'_{min}
		Annual	January	August	Annual	Annual
Sapporo	1881	2.6	3.6	1.1	0.8	4.5
Sendai	1025	2.3	3.2	0.4	0.8	3.1
Tokyo	8483	3.3	4.8	1.6	1.4	4.6
Niigata	785	2.1	2.7	1.4	1.9	2.3
Nagoya	2215	2.8	3.4	2.3	1.0	4.0
Osaka	2629	2.9	2.7	2.5	2.3	4.0
Hiroshima	1155	2.1	2.2	1.5	1.0	3.2
Fukuoka	1401	3.2	3.4	2.3	1.6	5.3
Kagoshima	604	3.0	3.5	2.6	1.3	4.3
17 stations[b]	–	1.5	1.9	0.8	0.9	1.8

[a] Data from JMA (2009).
[b] Same as those used for Figure 6.

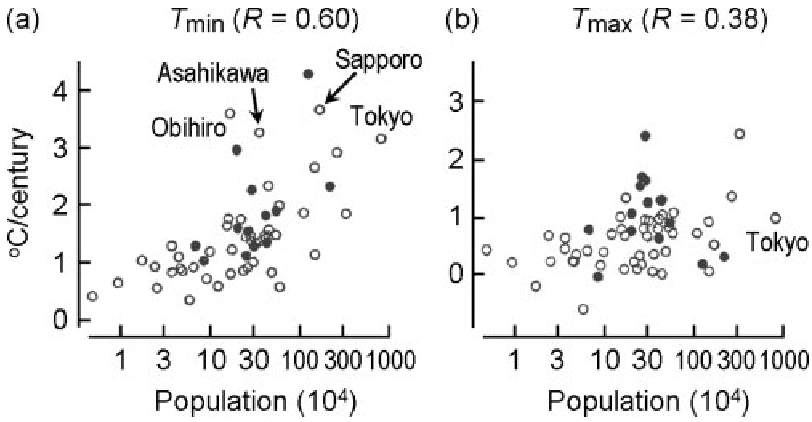

Figure 8. Relationships between (a) the trend of T_{min} and log P_{90} and (b) T_{max} and log P_{90} at 60 stations in Japan from 1891 to 1992 (from Fujibe, 1995). Closed circles indicate stations that have some uncertainty due to site changes, and open circles indicate other stations.

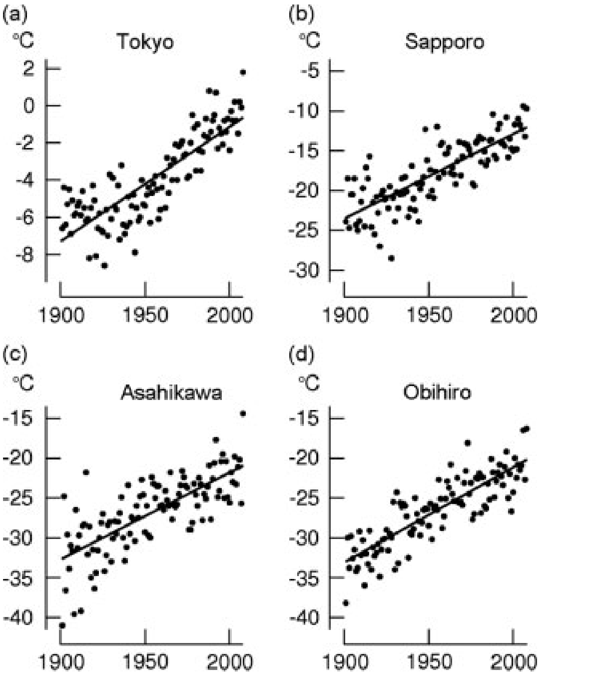

Figure 9. Time series of annual lowest temperature ($A_{\min}$) at Tokyo and the three stations in Hokkaido from 1901 to 2008. Lines indicate the linear regressions.

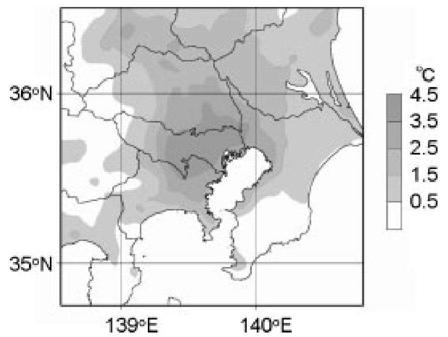

Figure 10. Temperature difference at 1400 JST between urban and non-urban locations in the Tokyo area, obtained from numerical simulation for a typical midsummer day in August (from JMA, 2005). The urban simulation includes anthropogenic heating and land use, with a simplified urban canopy parameterization. In the non-urban case, the urban surface was replaced by grass.

annexed later is included), which is 1/40 of the population in 2005. Asahikawa and Obihiro were nearly uninhabited at the beginning of the 20th century, and they offer ideal examples of a drastic change from uncultivated fields to medium-sized cities.

3. The extended heat island in the warm season

From the 1960s to the 1970s, air pollution in large urban areas became a serious problem, which resulted in the advancement of studies on local circulation, including dynamic aspects of the urban heat island (Kimura, 1975, 1976; Kimura *et al.*, 1977; Sawai, 1978). Converging surface wind patterns were detected in some cities, with stronger convergence during the daytime than at night in spite of the weaker urban–rural temperature contrast (Fujibe and Asai, 1980). Several observational studies have revealed a large thermal forcing on daytime heat islands, which may be less distinct in the surface temperature field but has a much larger vertical extent than nighttime heat islands (Yoshikado and Kondo, 1989; Yoshikado, 1990). For the past few decades, urban climatology studies in Japan have mainly targeted the heat load of cities in midsummer, whereas dynamic mesomodels parameterizing urban surface processes have been applied to numerical simulation of the urban atmosphere.

In central Japan, midsummer is characterized by sunny weather under the subtropical high-pressure systems, causing local circulation patterns to develop over the region. In the Tokyo area, sea breezes in the coastal area and inland valley breezes merge into an 'extended sea breeze' (Kondo, 1990a, 1990b) covering the Kanto Plain. Several numerical simulations have revealed a widespread urban-induced daytime temperature anomaly associated with this circulation pattern (Kimura and Takahashi, 1991; Kusaka *et al.*, 2000; Kusaka and Kimura, 2004). Figure 10 shows the differential temperature field for urban and non-urban cases at 1400 local time in August (JMA, 2005). The $\geq 1\,^{\circ}$C anomaly area is approximately 100 km, covering dozens of cities and the surrounding rural areas. This warming area, sometimes called the *extended heat island*, is far larger than that of the traditional heat island, which is confined to the area of a single city.

The mechanism of this widespread urban warming on the Kanto Plain has been explained in two ways. One is the large horizontal spread of the urbanized area (Figure 2), where the surface sensible heat flux is enhanced by reduced evapotranspiration. The other is a change in the wind field. The extended heat island spreads over the daytime mixing layer with a depth of about 1 km, with a pressure decrease of a considerable fraction of 1 hPa, causing intensified convergence in the central Kanto Plain. This convergence is likely to block the inland penetration of the sea breeze (Yoshikado, 1992, 1994; Kusaka *et al.*, 2000) and consequently the supply of relatively cool air to the inland area. In comparison, the effect of anthropogenic heat emission on the daytime warming appears to be small, except in central Tokyo (Kimura and Takahashi, 1991; Ichinose *et al.*, 1999; Kusaka and Kimura, 2004; Ohashi *et al.*, 2007).

Observational data show increased warm-season daytime temperatures in the inland part of the Kanto Plain. Figure 11 shows the distribution of $T_{\max}$ trends in July and August for a dense observation network that was in operation before deployment of the Automated Meteorological Data Acquisition System (AMeDAS; see Section 4). A warming region of $\geq 1\,^{\circ}$C over 30 years extends from the vicinity of Tokyo to the northwestern corner of the Kanto Plain, a finding that is in qualitative agreement with modelling results. A decrease in daytime pressure (relative to nighttime pressure) and a shift of wind direction towards the central Kanto Plain have also been

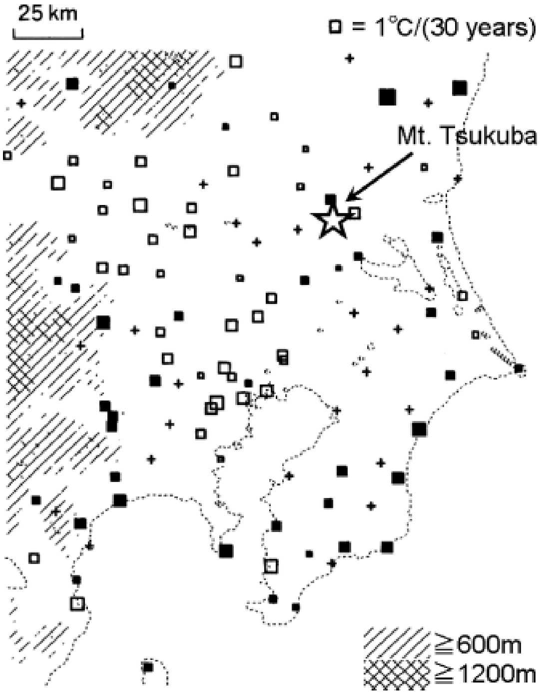

Figure 11. Trends of T_{max} (departure from Mt Tsukuba, 870 m a.s.l.) in July and August from 1946 to 1976. Open and closed squares indicate positive and negative changes, respectively, with their area proportional to the absolute values. Crosses indicate absolute values less than 0.2 °C over 30 years. Hatching indicates mountainous areas.

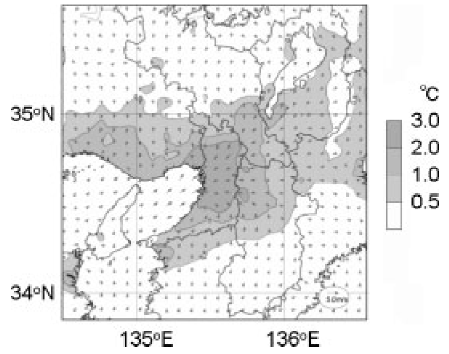

Figure 12. Same as Figure 10, but for 1500 JST on 5 August 2006 in the Osaka area (from JMA; http://www.data.kishou.go.jp/climate/cpdinfo/himr/2006/himr2006.pdf).

detected by analysis of long-term data (Fujibe, 1994, 2003).

Figure 12 shows the distribution of the urban anomaly in the Osaka region during the daytime in August (JMA; http://www.data.kishou.go.jp/climate/cpdinfo/himr/2006/himr2006.pdf). The topography of this region is different from that of Tokyo, in that it is a relatively small plain surrounded by mountains, but extensive urban warming is still observed over the three megacities of Osaka, Kyoto and Kobe. Ohashi and Kida (2002a, 2002b) described some peculiar circulation systems induced by the combination of topographical and urban effects in the region. In the Nagoya region, the situation is similar to that in the Tokyo area, reflecting the similarity of both the topographical setting and the local wind system (Kitada *et al.*, 1998).

4. Urban warming and climate change monitoring

The possibility of an urban bias in long-term temperature data is not limited to large cities, because a heat island can occur even in a small settlement with a population of 1000 or less (Tamiya, 1968; Oke, 1973; Tamiya and Ohyama, 1981; Sakakibara and Morita, 2002; Sakakibara and Kitahara, 2003; Sakakibara and Matsui, 2005). The 17 stations used by the JMA for climate monitoring (Figure 6 and Table I) were selected because they were 'considered not to have been much influenced by urbanization,' but some of the 17 stations are in cities with populations of more than 100 000 people, so that 'the analysis does not entirely eliminate the influence of urbanization' (JMA, 2009).

By the end of the 1970s, AMeDAS was deployed throughout Japan. This ground-based observation system provides hourly temperature data from a dense network of meteorological stations, including many at rural sites. Fujibe (2009b) used the AMeDAS data set to evaluate the urban anomaly in temperature trends in relation to population density. In this section, an analysis of the results of that study updated with recent data is presented.

The data period covered by Fujibe (2009b) is extended by 2 years to the 29 years from March 1979 to February 2008. Stations at which the percentage of days with missing data exceeded 3% of the total number of days for any one of the 12 months were not used (e.g. for January, a station was excluded if the number of days with undefined values was more than 27 over the entire period: 31 days $\times$ 29 years $\times$ 3% $=$ 27). To avoid the influence of discontinuities caused by site changes, stations that were moved a horizontal distance of 1 km or more or a vertical distance of 5 m or more were not used. In addition, some stations were removed from the analysis on the basis of an evaluation of the accuracy of spatial interpolation of rural temperature, as detailed by Fujibe (2009b). Figure 13 shows the distribution of the 546 stations selected for analysis. The linear trend, denoted by T', was calculated by least-squares regression. Further details of the analysis procedure are described by Fujibe (2009b).

Population distribution data were obtained from the 2000 census for grids of 30″ of latitude and 45″ of longitude (about 1 km $\times$ 1 km), compiled by the Ministry of Internal Affairs and Communications of Japan and distributed by Orkney, Inc. (Yokohama, Japan). The population density around station i was calculated from a weighted average:

$$P(i) = \frac{\sum_{g} \exp[-(r_{ig}/R)^2]P(g)}{\pi\ R^2} \tag{1}$$

where $P(g)$ is the population in grid g, r_{ig} is its distance from station i and $R = 3$ km.

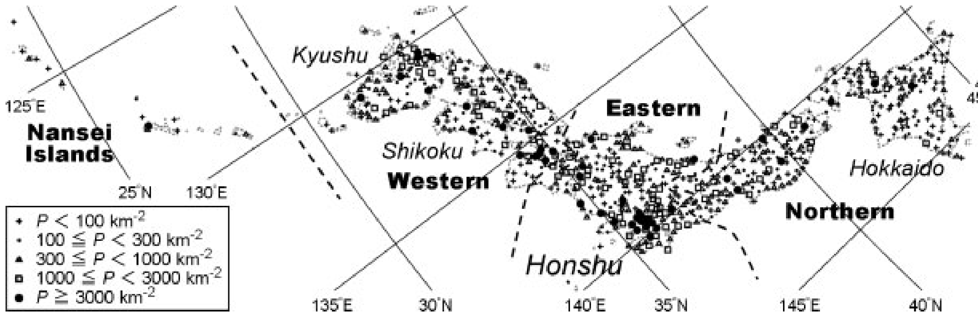

Figure 13. AMeDAS stations and the local population densities used for the analysis in Section 4. Dashed lines indicate the division of Japan into regions.

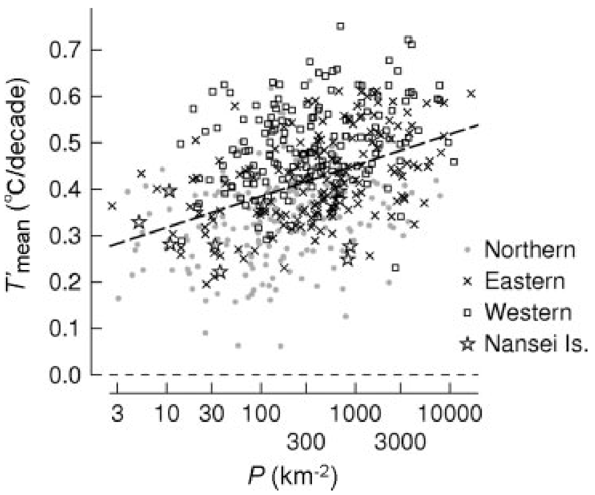

Figure 14. Plot of T'_{mean} *versus* log P at each station.

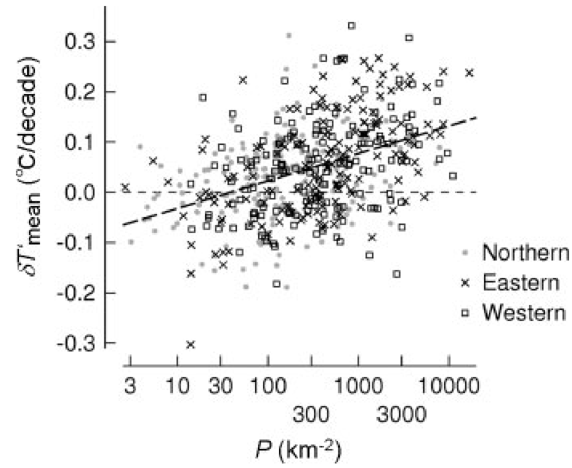

Figure 15. Plot of $\delta T'_{\text{mean}}$ *versus* log P at each station.

Figure 14 shows the relationship between the trends of daily mean temperature (T'_{mean}) and P. T'_{mean} and P are positively correlated with $r = 0.40$, indicating anomalous warming that is more rapid at stations with denser populations. However, even stations with $P < 100$ km^{-2} show a warming trend of about 0.3 °C decade^{-1}, which indicates the background climate change. In addition, there are some regional differences, with larger trends at stations in eastern and western Japan than in northern Japan.

To obtain the net urban trend, the departure of T' from its average for surrounding non-urban sites was calculated, on the assumption that regional warming was locally uniform. The averaging was based on spatial interpolation using the following least-squares condition:

$$\sum_j \exp[-(r_{ij}/r_0)^2]\{T'(j) - [a(i)x_{ij} + b(i)y_{ij} + T_0'(i)]\}^2 \to \min \qquad (2)$$

where x_{ij} and y_{ij} are eastward and northward distances from target station i to reference non-urban station j, ${r_{ij}}^2 = {x_{ij}}^2 + {y_{ij}}^2$, $r_0 = 300$ km, and $a(i)$, $b(i)$ and $T_0'(i)$ are least-squares coefficients. Here, stations with $P < 100$ km^{-2} were regarded as non-urban sites. Although some anomalous temperature trends were found even at stations with $P = 30–100$ km^{-2} (Fujibe, 2009b), these stations are treated as rural sites in this analysis to achieve adequate spatial coverage of reference stations, thus allowing for the possibility of a slight urban bias. The urban contribution in $T'(i)$ was defined by $\delta T'(i) = T'(i) - T_0'(i)$.

Figure 15 shows the relationship between $\delta T'_{\text{mean}}$ and P. Figure 16a shows the values of $\delta T'_{\text{mean}}$ averaged for each range of P. It can be seen that stations in densely inhabited areas ($P \geq 3000$ km^{-2}) have an anomalous trend of 0.12 °C decade^{-1}. Moreover, an anomalous trend of 0.03–0.05 °C decade^{-1} is detected even at stations with $P = 100–300$ km^{-2}. These findings confirm the presence of urban warming not only in large cities but also in small towns with a population density of 100–300 km^{-2}. Figure 16(b) and (c) shows the results for $\delta T'_{\text{max}}$ and $\delta T'_{\text{min}}$. At stations with $P < 1000$ km^{-2}, $\delta T'_{\text{max}}$ and $\delta T'_{\text{min}}$ are almost equal, whereas $\delta T'_{\text{min}}$ is substantially larger than $\delta T'_{\text{max}}$ at stations with $P \geq 1000$ km^{-2}. In other words, $\delta T'_{\text{min}}$ increases monotonically with population density (except in eastern Japan), whereas $\delta T'_{\text{max}}$ is largest around $P = 1000$ km^{-2}.

Figure 17 shows the seasonal and time-of-day dependence of $\delta T'$. At stations in densely inhabited areas ($P \geq 1000$ km^{-2}), $\delta T'$ has a distinct diurnal variation with a minimum around noon and a broad maximum

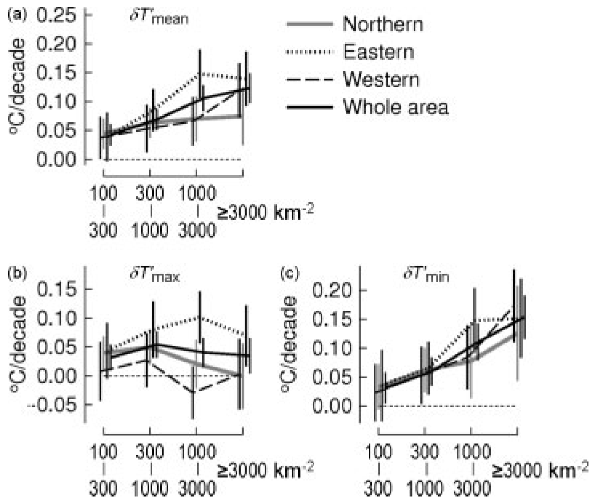

Figure 16. Dependence of $\delta T'_{mean}$, $\delta T'_{max}$ and $\delta T'_{min}$ on categories of population density, P. Vertical bars indicate 95% confidence ranges.

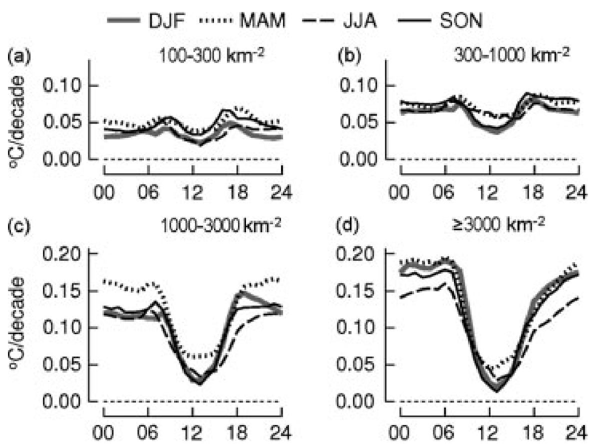

Figure 17. Time-of-day dependence of $\delta T'$ for each category of population density, P, and season (e.g. DJF represents December, January and February), based on an analysis covering the whole country.

at night, in agreement with the general observation that urban warming is more conspicuous at night than during the daytime. At stations at relatively sparsely inhabited sites ($P < 1000$ km^{-2}), $\delta T'$ has two peaks, in the morning and the evening. The diurnal variation patterns in $\delta T'$ are common among the four seasons with only a slight difference in peak time.

Urban warming on the order of 0.1 °C decade^{-1} also has been detected in other cities in eastern Asia (Jones *et al.*, 2008; Ren *et al.*, 2008; Kataoka *et al.*, 2009; Lai and Cheng, 2010), although urban signals in temperature trends may not be found in all countries of the world. The double-peak pattern of $\delta T'$ at stations with $P <$ 1000 km^{-2} (Figure 17) seems to be different from the typical cycle of the urban heat island characterised by a day–night contrast, but temperature changes of a similar diurnal variation pattern have been found to prevail over the United States, resulting at least in part from urbanization influences (Knappenberger *et al.*, 1996; Schwartzman *et al.*, 1998).

5. Microscale effects on observed temperature change

Various microscale factors can affect observed temperature change (Mahmood *et al.*, 2006; Runnalls and Oke, 2006; Pielke *et al.*, 2007). Kondo (http://www.asahi-net.or.jp/~rk7j-kndu/) has presented some observational evidence of temperature changes apparently related to changes in microscale environments such as construction of buildings, tree growth, reclamation and earthquake disaster. Kondo noted that a decrease in exposure to the wind is accompanied by a reduction of wind speed and upward heat diffusion, and results in a temperature increase. At the 19 stations that he selected, trends in temperature and wind speed showed a strong negative correlation. Fujibe (2009a) attempted a similar analysis using AMeDAS data gathered across the country, searching for statistical evidence of microclimatic effects on observed temperature trends. This section outlines the findings of that study.

The data and the analysis procedure are similar to those presented in Section 4. However, stations were required to satisfy stricter conditions with regard to site changes than those described in Section 4, because wind speed is highly sensitive to the site environment. Therefore, in this analysis, stations were excluded unless (1) the site had changed by a horizontal distance of less than 500 m and a vertical distance of less than 3 m and (2) the anemometer height had changed by less than 0.2 m. In addition, only stations with anemometer height below 10 m were used, so that the wind speed would represent the exposure to the wind at the screen height. As a result, 327 stations were used for the analysis. They are distributed across the whole country, except on the Nansei Islands, in the same manner as in the analysis of the previous section (Figure 13).

The temperature trend was calculated in the same way as in Section 4. The relative trend $\Delta U_i = \delta U_i/\overline{U}_i$, where i indicates the station, δU_i is the wind speed trend and $\overline{U}_i$ is the mean wind speed at station i, was used as the measure of the trend of wind speed. The average value of ΔU over the stations is -0.03 decade^{-1}, with a standard deviation of 0.09 decade^{-1}. Thus, wind speeds observed at AMeDAS stations have decreased on average, whereas the large variability among stations implies the dominance of local factors.

The analysis reveals that the relationship between $\delta T'$ and ΔU is dependent on the magnitude of $\overline{U}$. Figure 18 shows the relationship between $\delta T'_{max}$ and ΔU at stations with $\overline{U} \geq 1.5$ m s^{-1}. There is a weak but statistically significant correlation (r of about -0.2) between these parameters. Table II lists the correlation coefficients between $\delta T'$ and ΔU for specified ranges of $\overline{U}$. At stations with $\overline{U} \geq 1.5$ m s^{-1}, a significant negative correlation is found between $\delta T'_{max}$ and ΔU, and also between $\delta T'_{min}$ and ΔU for $P < 1000$ km^{-2} stations. However, $\delta T'$ and ΔU show no significant correlation at stations with $1.0 \leq \overline{U} < 1.5$ m s^{-1}. At stations with $\overline{U} < 1.0$ m s^{-1}, $\delta T'$ in the evening shows a relatively high correlation with ΔU (e.g. at 1800 JST in Table II),

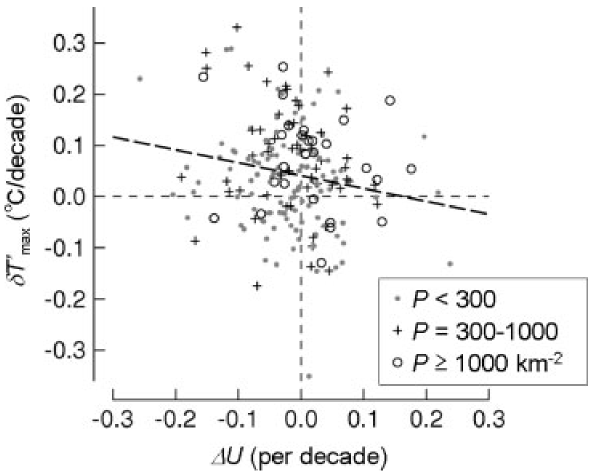

Figure 18. Relationship between $\delta T'_{\max}$ and ΔU at stations with $\overline{U} \geq 1.5$ m s^{-1}. The dashed line indicates the regression for all the stations plotted.

although $\delta T'_{\max}$, $\delta T'_{\min}$ or $\delta T'_{\text{mean}}$ show no significant correlation with ΔU.

Because $\delta T'$ is related not only to P but also to ΔU, the dependence of $\delta T'$ on P and ΔU was evaluated by applying a least-squares analysis in the form:

$$\sum_i [\delta T'_{ij} - (A_j + B_j \ \log_{10} \ P_i + C_j \ \Delta U_i)]^2 \rightarrow \min \quad (3)$$

where j indicates time of the day, and A_j, B_j and C_j are least-squares coefficients. The value of B_j gives the intensity of urban effects in the surrounding few kilometres, and C_j corresponds to microscale changes associated with the change in exposure. Figure 19 shows the time-of-day dependence of B_j and C_j, obtained by applying Equation (3) to stations with $\overline{U} < 1.0$ m s^{-1}, $1.0 \leq \overline{U} < 1.5$ m s^{-1}, $1.5 \leq \overline{U} < 2.0$ m s^{-1} and $\overline{U} \geq 2.0$ m s^{-1}. For all ranges of $\overline{U}$, B_j is significantly positive, with larger values at night than during the daytime, in agreement with the result presented in Section 4 (Figure 17). On the contrary, C_j has significant negative values of −0.2 to −0.3 °C around midday at stations with $1.5 \leq \overline{U} < 2.0$ m s^{-1} and $\overline{U} \geq 2.0$ m s^{-1}, consistent with the negative correlation of $\delta T'_{\max}$ and ΔU (Table II). At stations with $1.0 \leq \overline{U} < 1.5$ m s^{-1}, C_j is insignificant throughout the day, whereas stations with $\overline{U} < 1.0$ m s^{-1} show significant negative C_j values of −0.2 to −0.3 °C in the evening and weak positive values from morning to noon. An analysis of each season resulted in features that were essentially similar to that for the whole year described earlier (Fujibe, 2009a).

The dependence of the results on the mean wind speed implies different responses of temperature to changes in exposure to the wind, reflecting complicated mechanisms, both mechanical and radiational, in the surface layer. Thus, additional studies are needed to

Table II. Correlation coefficients between $\delta T'$ values and ΔU for specified ranges of $\overline{U}$.

		Number of stations	$\delta T'_{\max}$	$\delta T'_{\min}$	$\delta T'_{\text{mean}}$	$\delta T'_{18\ \text{JST}}$
$\overline{U} \geq 1.5$ m s^{-1}	$P < 300$ km^{-2}	112	−0.23[a]	−0.16	−0.14	–
	$P < 1000$ km^{-2}	168	−0.21[b]	−0.17[a]	−0.15	–
	All stations	195	−0.18[a]	−0.13	−0.08	–
$\overline{U} = 1.0$–1.5 s^{-1}	$P < 300$ km^{-2}	72	−0.17	−0.04	−0.04	–
	$P < 1000$ km^{-2}	89	−0.10	−0.08	−0.04	–
	All stations	94	−0.08	−0.05	−0.01	–
$\overline{U} < 1.0$ s^{-1}	$P < 300$ km^{-2}	27	0.27	−0.16	−0.05	−0.33
	$P < 1000$ km^{-2}	36	0.19	−0.21	−0.11	−0.33[a]
	All stations	38	0.16	−0.22	−0.13	−0.33[a]

[a] Significant at the 5% level.
[b] Significant at the 1% level.

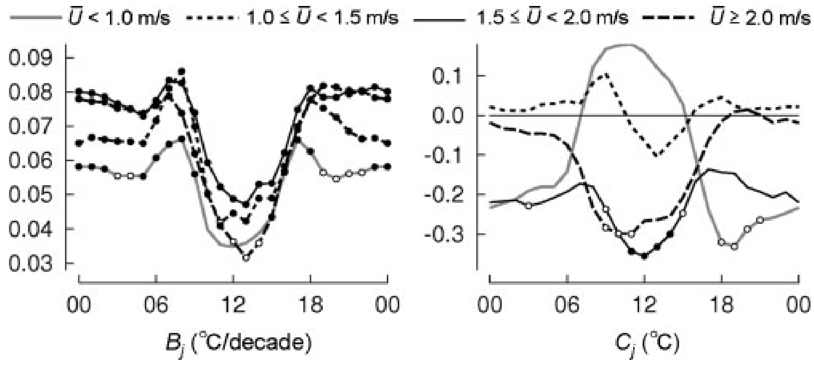

Figure 19. Time-of-the-day dependence of B_j and C_j defined by Equation (3) that was applied to stations in each range of $\overline{U}$ over the whole country. Open and closed circles indicate significance at the 5 and 1% levels, respectively.

quantify the causes of microscale temperature changes on the basis of detailed observations and numerical experiments.

6. Summary

Urban warming is quite conspicuous in large cities in Japan, reflecting their rapid growth during the last century. The temperature increase in Tokyo, where the meteorological observatory is located in the central business area of the city, has been about 3 °C century^{-1}. The warming rate is larger for nighttime (minimum) temperatures than for daytime (maximum) temperatures, in agreement with the general features of the urban heat island. In particular, the annual extreme minimum temperature has increased at a rate exceeding 10 °C century^{-1} in some cities in Hokkaido, corresponding to drastic changes from a small city or wild land to large or medium-sized cities at these sites.

Recent numerical studies have revealed widespread urban warming around Tokyo in the afternoon in summer. This feature, sometimes called the *extended heat island*, is explained by the enhanced surface heating over a large urban area, as well as a reduction of sea breeze penetration caused by increased surface convergence. A similar feature has also been found around other megacities such as Osaka and Nagoya, although there are some variations reflecting different topographical settings.

From the viewpoint of climate change monitoring, urban warming can be a biasing factor that may contaminate data used for monitoring the background temperature change. An analysis using 29 years of AMeDAS data revealed the existence of anomalous temperature changes, not only at densely inhabited sites but also at stations with relatively small populations in the surrounding areas. Even sparsely populated sites with population density of 100–300 km^{-2} show a statistically significant anomalous trend of 0.04 °C decade^{-1}.

For some ranges of mean wind speed and time of the day, the temperature trend was found to be correlated with the wind speed trend. This finding implies that microscale environmental changes may affect observed temperatures, reflecting complicated mechanical and radiational mechanisms in the surface layer.

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