Urbanization Effect on the Diurnal Temperature Range: Different Roles under Solar Dimming and Brightening*

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ABSTRACT

Based on the 1960–2009 meteorological data from 559 stations across China, the urbanization effect on the diurnal temperature range (DTR) was evaluated in this study. Different roles of urbanization were specially detected under solar dimming and solar brightening. During the solar dimming time, both urban and rural stations showed decreasing trends in maximum temperature (T_{max}) because of decreased radiation, suggesting that the dimming effects are not only evident in urban areas but also in rural areas. However, minimum temperature (T_{min}) increased more substantially in urban areas than in rural areas during the dimming period, resulting in a greater decrease in the DTR in the urban areas. When the radiation reversed from dimming to brightening, the change in the DTR became different. The T_{max} increased faster in rural areas, suggesting that the brightening could be much stronger in rural areas than in urban areas. Similar trends of T_{min} between urban and rural areas appeared during the brightening period. The urban DTR continued to show a decreasing trend because of the urbanization effect, while the rural DTR presented an increasing trend. The remarkable DTR difference in the urban and rural areas showed a significant urbanization effect in the solar brightening time.

1. Introduction

Diurnal temperature range (DTR) is an important climate factor. A downward trend of the global DTR since the 1950s has been well-documented in various studies (Easterling et al. 1997; Vose et al. 2005). It is widely recognized that changes in the clouds (Dai et al. 1999; Stone and Weaver 2003), aerosols (Huang et al. 2006; Stenchikov and Robock 1995), urbanization (Kalnay and Cai 2003), and solar radiation (Wild et al. 2007; Makowski et al. 2009) can largely affect the DTR. As described by Vose et al. (2005), the global DTR reduction slowed down since the 1980s because of the comparable increases of the maximum and minimum temperatures. Wild et al. (2007) attributed such change in the DTR to the reversing trend of global dimming to brightening in the 1980s. However, the phenomenon has continued since the mid-1980s, during which even a very slight decline in the DTR did not effectively respond to the brightening solar radiation.

We hypothesize that the urbanization effect played an important role in the decreasing DTR, especially during the solar brightening period. Urbanization alters the land use–cover and emits anthropogenic aerosols, which largely influence the local climate. The urban heat island shows a higher mean temperature in urban areas, and the DTR is commonly expected to decrease with urbanization. This urbanization impact has been estimated by comparing urban and rural observations (Gallo et al. 1999; Ren et al. 2008), observations minus reanalysis (Kalnay and Cai 2003; Zhou et al. 2004), and GCM simulations (Trusilova et al. 2008). Most of these studies covered both the dimming and brightening periods. Several studies indicated that the DTR was highly correlated with the surface solar radiation change. The DTR was decreasing before 1980s; however, the trend was reversed during the 1980s and showed an increasing trend after the 1990s in China and Europe, which is a coincidence with the decadal solar radiation change (Liu et al. 2004; Makowski et al. 2008). It seems that the solar radiation had a negative effect on the DTR during

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the dimming time and a positive effect during the brightening time. However, the impact of solar radiation under different solar radiation scenarios was hardly considered when studying the effect of urbanization on the DTR. The urbanization effect must be quantified separately during the dimming and brightening time.

In this study, the effects of solar radiation and urbanization on the DTR were examined. The urbanization effect on the DTR was specially detected during the solar dimming and brightening times. The daily mean, maximum, and minimum temperatures were also analyzed for comparison and for supplementary information. The results indicated that the effects of urbanization on the DTR were different during solar dimming and brightening times. The brightening solar radiation intensified the urbanization effect.

2. Data and methods

The daily mean (T_{mean}), maximum (T_{max}), and minimum (T_{min}) temperatures, and surface solar radiation (SSR) were taken from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn). The DTR was calculated as T_{max} minus T_{min}. All the data come from 756 meteorological observing stations, of which 122 stations had SSR measurements. For daily temperatures, the 559 stations that have records dated before 1960 were chosen, so that each station has more than a 50-yr period of data. For SSR, most of the stations began observation after the 1960s. The 52 stations that have records dated before 1961 were chosen. All the stations were well distributed across most of China. The annual average T_{mean}, T_{max}, T_{min}, DTR, and SSR were calculated by determining their average during the entire year. Years with missing data of more than one month were removed. We averaged the temperature data of the 559 stations and SSR data of the 52 stations to get the mean values for all of China. Average temperatures of the 52 stations were also calculated and compared with the averages of the 559 stations to determine if the 52 stations could represent the whole country. The correlation coefficients of T_{mean}, T_{max}, T_{min}, and DTR between these two datasets were 0.97, 0.99, 0.99 and 0.97, respectively. Therefore, the average SSR and temperatures of the 52 stations were representative of China.

The Fifth National Population Census data were obtained from the National Bureau of Statistics of China (http://www.stats.gov.cn/english/). The total urban population of the area, in which a station was located, was used to divide the stations into urban and rural stations. Stations in Inner Mongolia, Xinjiang, Tibet, Gansu, and Qinghai that were located in north and northwest China with a wide area and a sparse population density were eliminated to reduce the error resulting from regional differences. After these steps, 402 stations remained, covering the period of 1960–2009. The definitions for each station category and its quantity are listed in Table 1. The distribution of these stations is exhibited in Fig. 1. Thus, the urbanization effect was studied by comparing the regression trends of urban (large and small cities) and rural station observations. Based on the analysis of solar radiation change (Fig. 2) and some previous studies about the SSR in China (Liu et al. 2004; Ye et al. 2010; Xia 2010), the time series was subdivided into two periods. One was from 1960 to 1989 and the other was from 1990 to 2009, which represents the dimming and brightening times, respectively. The urbanization effect on the DTR was further investigated under different solar radiation conditions.

TABLE 1. Number of stations for each category.

	Large city	Small city	Rural
Urban population ($\times 10^4$)	$\geq$50	5–50	<5
Number of stations	71	234	97
Number of stations in the five eliminated provinces	5	50	102

3. Results and discussion

a. *Solar radiation change and its effect on DTR*

Based on the 52 meteorological stations with long-term SSR observations, we have investigated the solar radiation change and its impact on temperature trends. The result reveals an obvious decreasing trend in solar radiation from 1960s to 1980s. After the 1990s, the SSR began to show an increasing trend (Fig. 2). From 1961 to 1989, the solar dimming rate was -0.70 MJ m^{-2} decade^{-1} and the brightening rate was 0.24 MJ m^{-2} decade^{-1}.

During the period of 1961–89, T_{max} got cooler (-0.06°C decade^{-1}) because of less solar radiation. But T_{mean} (0.05°C decade^{-1}) and T_{min} (0.24°C decade^{-1}) showed increasing trends, likely because of the impact of the greenhouse effect. The DTR was significantly negative during this period (-0.31°C decade^{-1}). During the period of 1990–2009, when the solar radiation reversed from dimming to brightening, T_{mean}, T_{max}, and T_{min} all increased dramatically, at a rate above 0.37°C decade^{-1}. The DTR showed a much more moderate decreasing trend (-0.03°C decade^{-1}). Solar brightening enhanced the temperature warming and mitigated the DTR from decreasing during this period (Fig. 3).

It has been reported that the DTR was highly correlated with the surface solar radiation change (Liu et al. 2004; Makowski et al. 2008). Here we examined the relationship between solar radiation and the diurnal temperature range (Fig. 4). The correlation coefficient

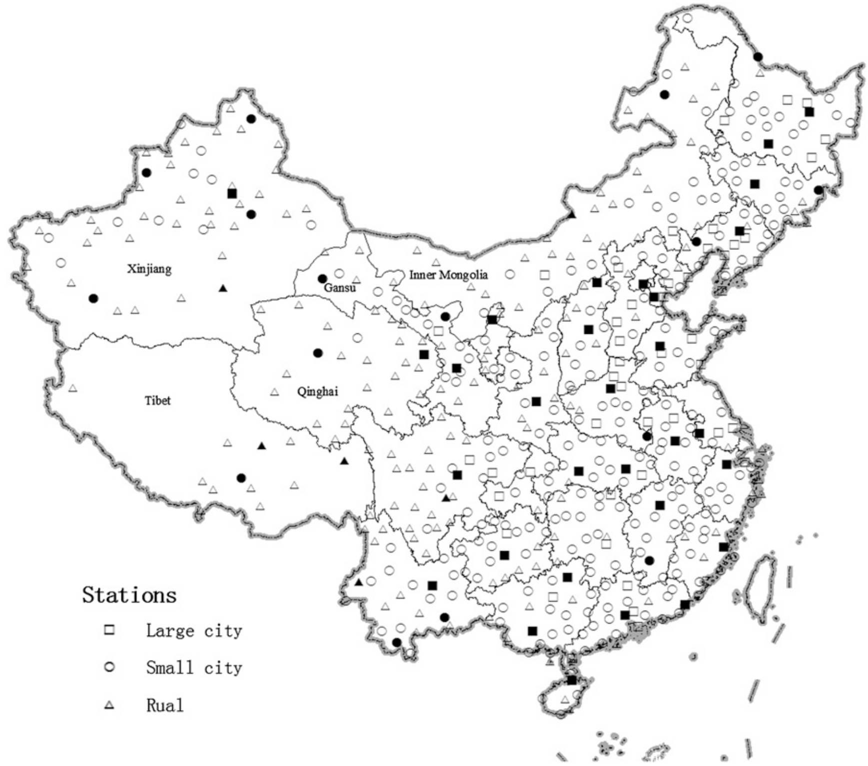

FIG. 1. Distribution of meteorological stations. Filled symbols are stations with radiation measurements.

between the DTR is 0.78 (significant at the 0.01 level) during the entire period, suggesting that the DTR is consistent with the surface solar radiation change. Similar results can be revealed in different regions of China (see supplemental materials, Table S1; Fig. S1). However, the correlation coefficient was much higher (0.88, significant at the 0.01 level) during 1961–89, suggesting that solar dimming played an important role in decreasing the DTR. During 1990–2009, solar radiation increased, while the DTR decreased. This discrepancy indicated that other factors, such as urbanization, might have a substantial impact on the DTR during this period.

b. Urbanization effect from 1960 to 2009

For comparison, the urbanization effect during the period from 1960 to 2009 was analyzed first. The average trends of temperatures in the urban and rural stations are listed in Table 2. It is evident that the T_{mean} in cities increased slightly faster than in rural sites (from 0.28° to 0.24°C decade^{-1}). On the contrary, the DTR in cities decreased much faster than in rural sites (from −0.18° to −0.06°C decade^{-1}). This apparently shows the urbanization effect. The $T_{\max}$ in cities increased slower than in rural sites (from 0.19° to 0.22°C decade^{-1}), while the $T_{\min}$ increased faster in urban sites (from 0.38° to 0.28°C decade^{-1}). This phenomenon is possibly due to the cooling effect during the daytime and the longwave radiation during the nighttime, induced by urban anthropogenic aerosols. In addition, the nighttime thermal release from the impermeable land in the cities also made the $T_{\min}$ increase faster than in rural areas.

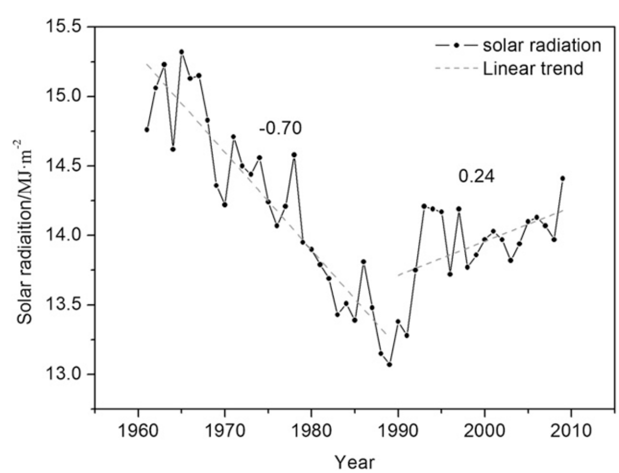

FIG. 2. Annual solar radiation change of 52 stations from 1961 to 2009. Dashed lines are linear trends of two periods: 1961–89 and 1990–2009; values are the rates of change (MJ m^{-2} decade^{-1}).

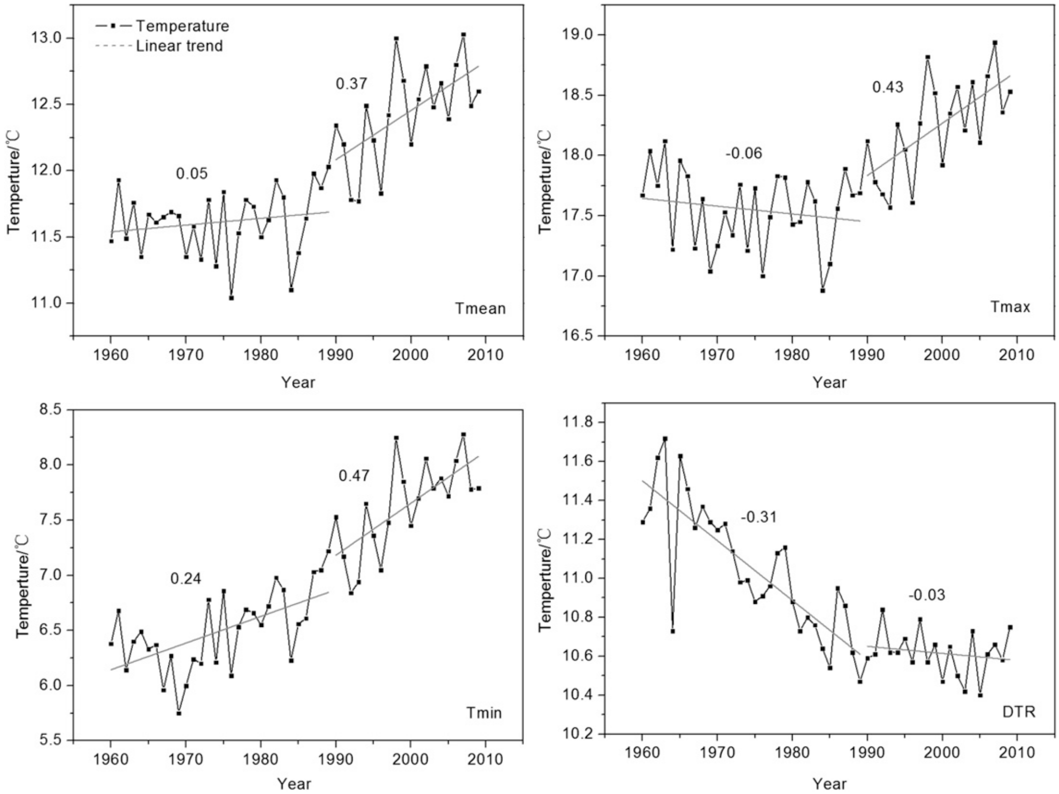

FIG. 3. Annual (top) (left) T_{mean} and (right) T_{max}, and (bottom) (left) T_{min} and (right) DTR of the 52 SSR stations from 1960 to 2009. Dashed lines are linear trends of two periods: 1960–89 and 1990–2009; values are the rates of change (°C $decade^{-1}$).

c. Urbanization effect under solar dimming and brightening

The average trends of temperatures in the divided periods are listed in Table 3. The years 1960–89 and 1990–2009 represent the dimming and brightening times, respectively. During the solar dimming time, the T_{max} of both urban and rural sites showed decreasing trends, which resulted from the decline of solar radiation coming to the earth. Because of the greenhouse effect, the T_{mean} increased slightly, while the T_{min} increased more significantly. Like the time series of 1960–2009, an obvious urbanization effect is revealed by the faster increase in T_{mean} (from 0.07° to 0.01°C $decade^{-1}$) and the decrease in the DTR (from −0.30° to −0.16°C $decade^{-1}$) in the urban sites during this period. From 1990 to 2009, which is the solar brightening time, the T_{max}, T_{mean}, and T_{min} all increased dramatically because of the increase in radiation heating. However, unlike the former period, the T_{min} changed in a parallel trend in the city and rural areas. Furthermore, a larger increase in the trends of the T_{mean} and T_{max} appeared in rural sites during this period. Then, the DTRs of the rural sites rose (0.17°C $decade^{-1}$), while in the urban sites the decreasing trends (−0.02°C $decade^{-1}$) continued.

Therefore, different roles of the urbanization effect can be found under solar dimming and solar brightening. For the T_{mean}, urbanization produced a positive effect during the dimming time and a negative effect during the brightening time. However, the effects in both periods were subtle. For the DTR, the difference between the two periods seems to be more evident. During the solar dimming time, the DTR over all the land supposedly

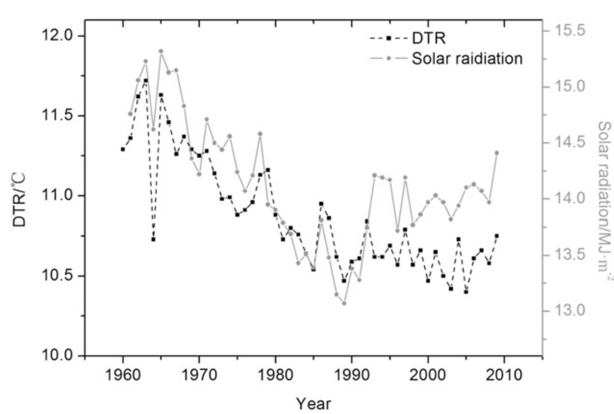

FIG. 4. Relationship between DTR and solar radiation.

TABLE 2. Linear trends of T_{mean}, T_{max}, T_{min}, and DTR from 1960 to 2009 (°C decade^{-1}). Number of stations in each category as in Table 1. Average is the mean value of 402 stations. All numbers are significant at the 0.01 level when using *t* test.

	Large city	Small city	Rural	Average
T_{mean}	0.28	0.24	0.23	0.24
T_{max}	0.19	0.18	0.22	0.19
T_{min}	0.38	0.32	0.28	0.32
DTR	−0.18	−0.14	−0.06	−0.13

declined because of the reduction in solar radiation. The urban sites showed a faster decreasing trend because of the urbanization effect. In comparison with the rural DTR change, the urbanization impact on the DTR resulted mostly in the amplification of the decreasing trend of T_{max} and the increasing trend of urban T_{min} during this period. Moreover, during the solar brightening time, the DTR in all of the land supposedly rises because of the augmentation in solar radiation and so does the rural DTR represented. However, the urban DTR continued showing a decreasing trend that can be totally attributed to the urbanization effect. Urbanization mostly resulted in diminishing the increasing trend of urban T_{max} (Fig. 5). The remarkable difference in the DTR can be found in the urban and rural areas during this time, revealing a significant urbanization effect.

Reports stated that the anthropogenic aerosols were responsible for the solar dimming and brightening (Streets et al. 2006; Ohmura 2009; Wild 2009). The dimming may result from the radiation scattering and absorption effects by aerosols, which also makes daytime temperatures cooler. For T_{max}, the comparable decreasing trends of T_{max} indicated similar solar dimming in the rural and urban areas. As described by Alpert et al. (2005), solar dimming was highly affected by population–urbanization. Further studies indicated that solar dimming was observed to be restricted to highly populated sites with a population density higher than 10 persons per square kilometer (Alpert and Kishcha 2008). Wild (2009) summarized that global dimming and brightening is a larger-scale phenomenon. This result showed that solar dimming was not only seen in the urban areas but also in rural areas. According to the maximum temperature change after the 1990s in this study, the brightening has indeed happened in China after the 1990s. But, other facts, such as land use change, could also enhance the daytime temperature warming (Zhou et al. 2004). Whether the brightening happened in urban or rural areas still needs further study. The urbanization effect on dimming and brightening in China was rarely studied because of the lack of stations with SSR data. This study can provide indirect evidence of different dimming and brightening trends in urban and rural areas of China.

TABLE 3. Linear trends of T_{mean}, T_{max}, T_{min}, and DTR in two periods (°C decade^{-1}). Number of stations in each category as in Table 1. Average is the mean value of 402 stations. Boldface numbers are significant at the 0.01 level when using *t* test.

		Large city	Small city	Rural	Average
1960–89	T_{mean}	0.07	0.01	0.01	0.02
	T_{max}	−0.09	−0.12	−0.07	−0.10
	T_{min}	**0.21**	0.13	0.10	0.13
	DTR	**−0.30**	**−0.25**	**−0.16**	**−0.24**
1990–2009	T_{mean}	**0.38**	**0.36**	**0.44**	**0.39**
	T_{max}	**0.40**	**0.42**	**0.58**	**0.46**
	T_{min}	**0.41**	**0.39**	**0.42**	**0.40**
	DTR	−0.02	0.02	**0.17**	0.05
Relative change	T_{mean}	+0.31	+0.35	+0.43	+0.37
	T_{max}	+0.49	+0.54	+0.65	+0.56
	T_{min}	+0.20	+0.26	+0.32	+0.27
	DTR	+0.28	+0.27	+0.33	+0.29

Another result that should be considered is that the similar trends of T_{min} between urban and rural areas appeared in the brightening period. During the dimming period, a larger decreasing trend of T_{min} occurred in the urban stations, suggesting an urbanization effect in these areas. During the brightening period, it is hard to distinguish the impact of land use–cover according to the comparable trends of T_{min} in urban and rural areas. Considering that the maximum temperature increased faster in rural areas, the brightening could be much stronger in rural areas than in urban areas. The rural areas received more solar heating, making daily temperatures (including T_{max}, T_{min}, and T_{mean}) higher. At the same time, urban T_{min} was influenced by urbanization, which made the nighttime temperature warmer. Rural T_{min} was dominated by the larger brightening solar radiation, while urban T_{min} was dominated by the

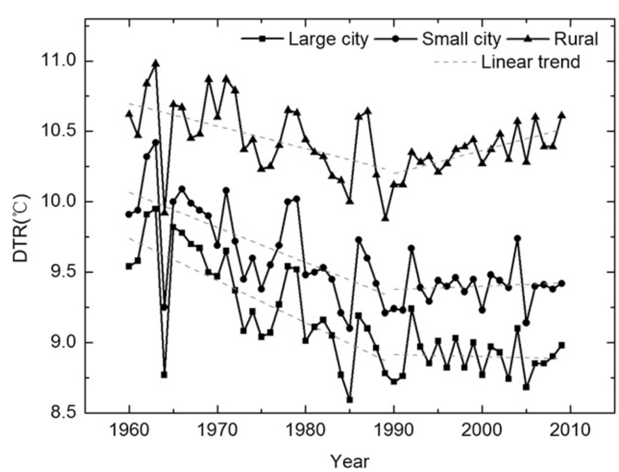

FIG. 5. DTR changes of the large city, small city, and rural stations.

urbanization effect. Both factors can enhance the nighttime warming, resulting in the comparable trends of T_{min} in this period. The same reason could explain the smaller increasing trend of T_{mean} in the urban areas during this period. Since land use–cover produce a positive effect and aerosols produce a negative effect on urban climate, the contribution of land use–cover change and aerosol radiative forcing to the urbanization effect during dimming and brightening still needs further study.

4. Conclusions

In this paper, the urbanization effect on the DTR was investigated. In the time series from 1960 to 2009, an obvious urbanization effect was seen in the urban sites compared with the rural sites. The DTR decreased faster in urban than in rural stations. Considering the solar radiation change, further studies were carried out to determine the different roles in which urbanization played under solar dimming and solar brightening. During the solar dimming time, the T_{max} in all stations showed a decreasing trend, while the T_{min} showed an increasing trend. Moreover, the T_{min} in urban stations increased faster than in rural stations because of the urbanization effect. At the same time, the DTR was decreasing faster in the city areas. As the radiation turned to brightening, the T_{max} and T_{min} were all increasing dramatically. Unlike in the dimming time, the T_{max} was increasing faster in the rural places, while the T_{min} was increasing in a similar trend in urban and rural places. These results lead to the decreasing DTR in the urban areas and an increasing DTR in the rural areas. The remarkable difference in the DTR shows a significant urbanization effect in this period.

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