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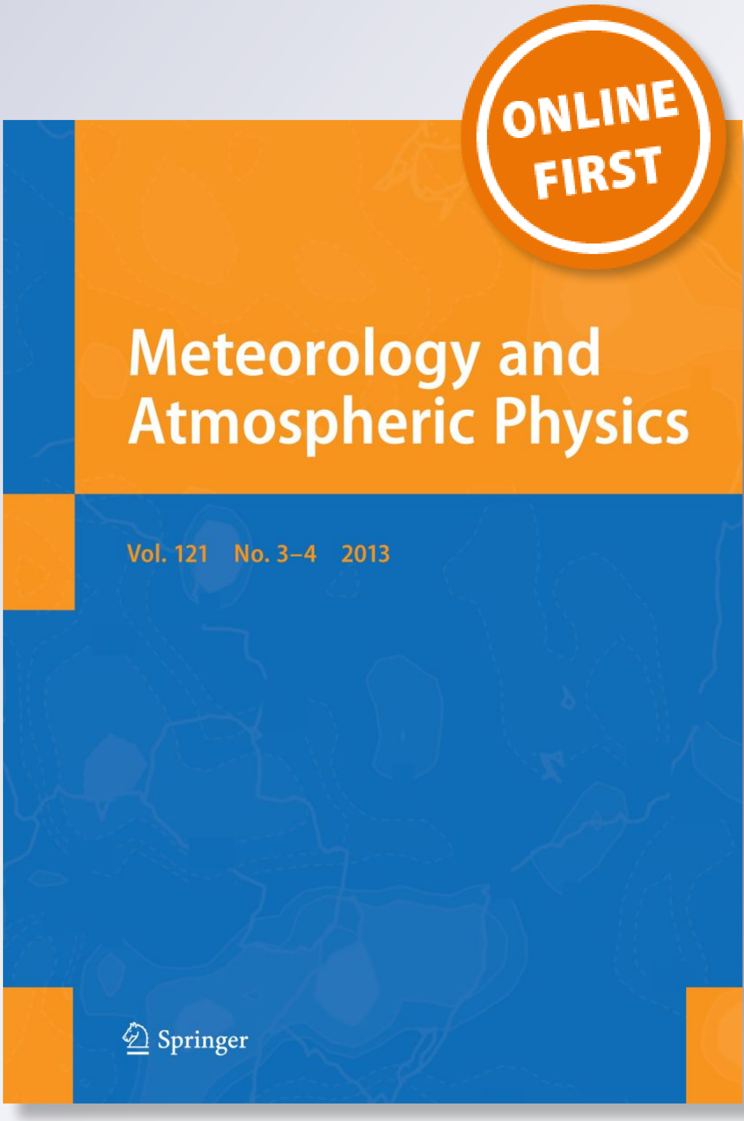

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ORIGINAL PAPER

Reassessment of urbanization effect on surface air temperature trends at an urban station of North China

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Abstract Based on a homogenized data set of monthly mean temperature, minimum temperature, and maximum temperature at Shijiazhuang City Meteorological Station (Shijiazhuang station) and four rural meteorological stations selected applying a more sophisticated methodology, we reanalyzed the urbanization effects on annual, seasonal, and monthly mean surface air temperature (SAT) trends for updated time period 1960–2012 at the typical urban station in North China. The results showed that (1) urbanization effects on the long-term trends of annual mean SAT, minimum SAT, and diurnal temperature range (DTR) in the last 53 years reached 0.25, 0.47, and − 0.50 °C/decade, respectively, all statistically significant at the 0.001 confidence level, with the contributions from urbanization effects to the overall long-term trends reaching 67.8, 78.6, and 100%, respectively; (2) the urbanization effects on the trends of seasonal mean SAT, minimum SAT, and DTR were also large and statistically highly significant. Except for November and December, the urbanization effects on monthly mean SAT, minimum SAT, and DTR were also all statistically significant at the 0.05 confidence level; and (3) the annual, seasonal, and monthly mean maximum SAT series at the urban station registered a generally weaker and non-significant urbanization effect. The updated analysis evidenced that our previous work for this same urban station had underestimated the urbanization effect and its contribution to the overall changes in the SAT series. Many similar urban stations were being included in the current national and regional SAT data sets, and the results of this paper further indicated the importance and urgency for paying more attention to the urbanization bias in the monitoring and detection of global and regional SAT change based on the data sets.

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1 Introduction

The development of city leads to tremendous change in urban underlying surface, and this will affect the surface energy budget, which will in turn result in the rise of surface air temperature (SAT) in the urban area. The phenomenon is generally called Urban Heat Island (UHI) (Kukla et al. 1986; Oke 1987; Xu et al. 2002; Grimmond 2006). The effect of UHI and its change with time have been recorded by the meteorological stations in the cities and their suburbs, and the systematic bias in the SAT data has been produced for many climatic stations across mainland China, and probably on a larger spatial scale (Ren et al. 2010). In the late 1980s, people began to realize the importance of the urbanization bias for the detection of the regional temperature change. For example, Karl et al. (1988) found that the effect of UHI on the SAT change at the US city stations was very evident during 1901–1984 by comparing and analyzing the SAT trends of urban and suburban stations in America; Balling and Idso (1989) discovered that the SAT in the eastern America during 1920–1984 increased 0.39 °C, but it rose only 0.02 °C if the urbanization effect was excluded; Based

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on the urban–rural SAT data in China in 1954–1983, Wang et al. (1990) found that the influence of UHI was obvious; Zhao (1991) indicated that urbanization effect on SAT trends in China could not be ignored, after she analyzed the annual mean SAT change for varied categories of observational stations for the last 39 years. By comparing the average SAT change of the urban and rural stations in the former Soviet Union, eastern China, eastern Australia, and America, however, Jones et al. (1990, 2008) reported a very small urbanization effect in the SAT data series in these areas, and even a relatively increased temperature for the rural stations in eastern China.

In the last 10 years, Chinese researchers conducted a series of works (e.g., Ren et al. 2005, 2007, 2008; Hua et al. 2008; Zhang et al. 2010; Ren and Ren 2011; Wang and Ge 2012; Yang et al. 2011, 2012; He et al. 2013; Li et al. 2013; Wu and Yang 2013), showing significant urbanization effects on the records of the SAT in the regional and local scales. Zhang et al. (2010) showed, for example, that the urbanization contribution to the overall warming trends was above 27% during 1961–2004 in terms of the country-averaged annual mean SAT for the national reference climatic stations and the basic meteorological stations, which are generally applied in studies of climate change. Besides eastern and northern China, and mainland China on a whole, urbanization also has important effects on long-term trends of mean temperature and heat waves in southern China, particularly in the Pearl River Delta region (e.g., Wang et al. 2014; Luo and Lau 2017).

In mainland China, relocations of stations have been found to be a major factor for producing discontinuity of the SAT data. It has also been realized that it is not an easy task to adjust the data inhomogeneities, and new systematic bias can result if the homogenizations were conducted for the urban stations experiencing relocations from built-up areas to suburban or rural areas, leading to a larger urbanization effect in the adjusted data series (Zhang et al. 2014; Li et al. 2014). As a national basic meteorological station, Shijiazhuang station has never experienced the relocation until January 2013 when it was moved to a rural site. The data from this station thus avoided in a large extent the uncertainty from inhomogeneities before 2013, benefiting a study of other uncertainties in observations including the urbanization bias. The historical data from this station have also been frequently used in the analyses of climate change in China for varied spatial scales (e.g., Zhai and Ren 1997; Ren et al. 2005, 2010; Bian and Lian 2008; Bian et al. 2012, 2015), and it is thus essential to understand in what extent the SAT data series of the urban station had been affected by urbanization during the past six decades.

In our previous studies, we found that the urbanization effect on the SAT trends at this urban station was significant (Bian et al. 2012, 2015), with the annual mean urban warming reaching 0.19 °C/decade, and the urbanization contribution to the overall warming trend reaching 67.9%. In the previous studies, however, the SAT data of the rural stations had not been adjusted for inhomogeneities, and the four rural stations were not really located in the rural areas, making them less representative as reference sites.

This paper updates the analysis of the urbanization effect on the SAT trends at Shijiazhuang station, using the homogenized data recently released by the National Meteorological Information Center, China Meteorological Administration (CMA), and four new rural stations selected through a more sophisticated method developed by our group (Ren et al. 2015). The analysis results from this paper are somehow different from those reported in our previous papers, but they are more accurate and robust. The results can be used after adjustment of the systematic bias in monitoring and studies of regional climate change, and can also be referred in studies of urban climate and urban climate change.

2 Data and methods

Homogenized data for mean monthly, maximum, and minimum temperature, available from the National Meteorological Information Center, CMA, for 1960–2012, were used in this study. The target station was Shijiazhuang (No 53698), while reference (rural) stations were selected from the 143 stations across the mainland China, which were developed by Ren et al. (2015). Shijiazhuang, the capital city of Hebei Province, is located in the east of the Taihang Mountains and on the west of the North China Plain, and has experienced rapid urbanization in the past 20–30 years. Shijiazhuang station was located in the mid-west of the city. It was initially a suburban station, but was moved in 2013, because it had become a typical urban station (Fig. 1). The station has been one of the national basic meteorological stations in China and provides surface climate data to the national observational network.

A comprehensive procedure was applied to develop the reference station network, taking such indicators into consideration as record length and completeness, times of relocations, population of the settlements, where the stations are located, and the ratio of artificial buildings to circular areas with 2-km radius from observational grounds of the stations (Ren et al. 2015). The method used for determining the four specific reference sites was to select all reference stations (10 in total) within a radius of 500 km around Shijiazhuang station, and then to calculate the correlation coefficient of the annual mean SAT between each station and Shijiazhuang station. The correlations were 0.91, 0.82, 0.77, and 0.71 (all statistically significant test at the 0.05 level) for Yanshan station, Yushe station, Qingshuihe station, and Shangdianzi station, respectively. The radius of 500 km

Fig. 1 Distribution of stations and a satellite map showing the state of the environment around Shijiazhuang station (code no 53698)

around Shijiazhuang station was applied mainly considering the fact that this study was to examine the observational bias of large-scale climate change, and the spatial consistency of surface air temperature trends is generally high (Jones et al. 1997; Hansen et al. 2010; Ren et al. 2015). Therefore, although the far-away reference stations may introduce the uncertainties related to the spatial variations of local climate background, they are not too far and still within a distance of 500 km, and they are representative and applicable for the purpose to differentiate the locally urbanization effect from regional scale background change in surface air temperature in this region. The details of all the stations used are shown in Table 1 and Fig. 1.

It is also notable that one reference station (Shangdianzi) is closer to Beijing urban areas than the other reference stations, but it is not located in built-up areas and has not experienced any influence of urbanization and any relocation responsible for inhomogeneities of temperature data over the last decades. Actually, it is located in the hill areas of northeastern part of Beijing Municipality, and it was ever chosen

Table 1 Details of the urban and reference meteorological stations used in this and previous studies

Type	Code no	Name	Longitude (E) (°)	Latitude (N) (°)	Altitude (m.a.s.l.)	Start time	Time of relocation
Urban station	53698	Shijiazhuang	114.42	38.03	81.0	1955.01.01	2013.01.01
Reference stations used in this study	54627	Yanshan	117.14	38.02	8.8	1957.01.01	1961.01.01, 1980.01.01
	53562	Qingshuihe	111.40	39.55	1190.8	1959.01.01	1965.01.01
	54421	Shangdianzi	117.07	40.39	286.5	1958.01.01	1988.01.01
	53787	Yushe	112.59	37.04	391.8	1957.01.01	None
Reference stations used in the previous study	53697	Gaocheng	114.81	38.01	53.5	1958.08.01	1969.07, 1999.01
	53791	Yuanshi	114.53	37.75	66.4	1960.01.01	1982.02, 1998.01, 2007.01
	53694	Pingshan	114.02	38.25	131.0	1959.01.01	1961.09, 1964.01, 2000.01
	53695	Xinle	114.68	38.35	70.8	1959.03.01	1961.05, 1963.12, 1989.05, 2003.01

m.a.s.l. meters above sea level

as a rural station in the previous studies (Chu and Ren 2005; Ren and Zhou 2014). Overall, the long continuous data series from the four reference stations are representative of rural areas with a very small residential population far from metropolitan areas, and the observational settings around the stations are relatively open and good.

The mean reference SAT series was obtained from the weighted average of the monthly mean SAT at the four rural stations, with the square roots of the correlation coefficients used for the weightings. Before establishing the mean reference series, SAT anomalies for each station were computed to avoid the impacts of the altitude differences among the stations. The anomalies were the differences of the monthly mean SAT from the averages of 1981–2010. Data of the urban population of Shijiazhuang City were taken from the Statistical Yearbook on Urban Regional Development Planning for Shijiazhuang. The SAT trends were obtained using the linear regression equation $x_i = a + bt_i$ ($i = 1, 2, 3,\ldots n$), where a is the constant and b is the regression coefficient. b*10 is the linear trend or change rate of the SAT, with the unit being °C/decade (Wei 2007). The regression coefficient b or b*10 quantitatively reflects the linear trend of SAT over time. The values of a and b were estimated using the least square method. The correlation coefficients of the SAT series with sequence numbers of years were also calculated to verify the nature and magnitudes of the trends and to determine the significance of the SAT trends. The autocorrelation might affect the uncertainty interval 95% of the trend, which might have an effect on the significance test, but might not influence the best estimate (Qian 2016). Therefore, the possible impact of the serial correlation had been considered in the estimation of statistical significance. The method of polynomial fitting was adopted to fit the temperature anomaly difference series in this paper, and the order was determined as 3. This was made with a purpose to exhibit the low-frequency or decadal variations in the data series.

The following terms were defined with reference to Ren et al. (2007), Ren and Zhou (2014), Bian et al. (2015):

Urbanization effect This refers to the linear trends in temperature recorded at an urban station that are caused by an increase in the intensity of the UHI and/or other local anthropogenic factors. It is expressed as ΔT_{u-r}:

$$\Delta T_{u-r} = T_u - T_r, \tag{1}$$

where T_u is the linear trend of a temperature series at an urban station, and T_r is the linear trend of the average temperature series at the rural stations. If $\Delta T_{u-r} > 0$, the temperature series at the urban station has an upward change in relation to that of the rural station due to the urbanization effect. If $\Delta T_{u-r} < 0$, the temperature series at the urban station has a downward change in relation with that of the rural station due to the urbanization effect. The linear trend of the temperature anomaly difference series between the urban station and the rural stations, which was also used in this paper, is actually another expression of the urbanization effect, and it is equal to ΔT_{u-r}. The correlation coefficients of the temperature anomaly difference series with sequence numbers of years thus were used to determine the statistical significance of the urbanization effect.

Urbanization contribution This refers to the proportion of the statistically significant urbanization effect to the overall trend of the SAT series at the urban station. It is expressed as C_u (%):

$$C_u = \left|\Delta T_{u-r}/T_u\right| \times 100\%. \tag{2}$$

Because the urbanization effect can be negative in certain circumstances, an absolute value was taken for C_u to enable $0 \le C_u \le 100\%$. If $C_u = 0$, the urbanization effect makes no contribution to the overall trend of the temperature series at the urban station. If $C_u = 100\%$, the linear trend of the temperature series at the urban station is caused entirely by the urbanization effect. In practical calculations, C_u may sometimes exceed 100% in case of the decreasing trend of the rural temperature or the increasing trend of the rural DTR, indicating that unknown local anthropogenic factors might have an effect on the reference sites, but it was adjusted to 100% in this study. As the definition implies, the urbanization contribution was not calculated if urbanization effect was not statistically significant.

The seasonal division used in this study was as follows: spring (March, April, May), summer (June, July, August), autumn (September, October, November), and winter (December, January, February). The data for winter 1960 were collected from December 1959 to February 1960.

3 Results

3.1 Changes in SAT at Shijiazhuang station

The annual mean SAT anomaly series at Shijiazhuang station showed that, during 1960–2012, there was a significant upward trend in the annual mean temperature at the national station. The rate of increase was 0.36 °C/decade, which was significant at the 0.001 level, and a more rapid annual mean warming occurred after the mid-1990s (Fig. 2). The large increase after the mid-1990s might be caused by the rapid expansion of the urban areas to the surrounding zone of the station. The station was far from the built-up areas when it was established and during the earlier decades, but by the mid-1990s, the high-buildings appeared around the station, and now, it had become a typical urban station surrounded by large amount of built-up areas by a few years ago (Bian et al. 2012).

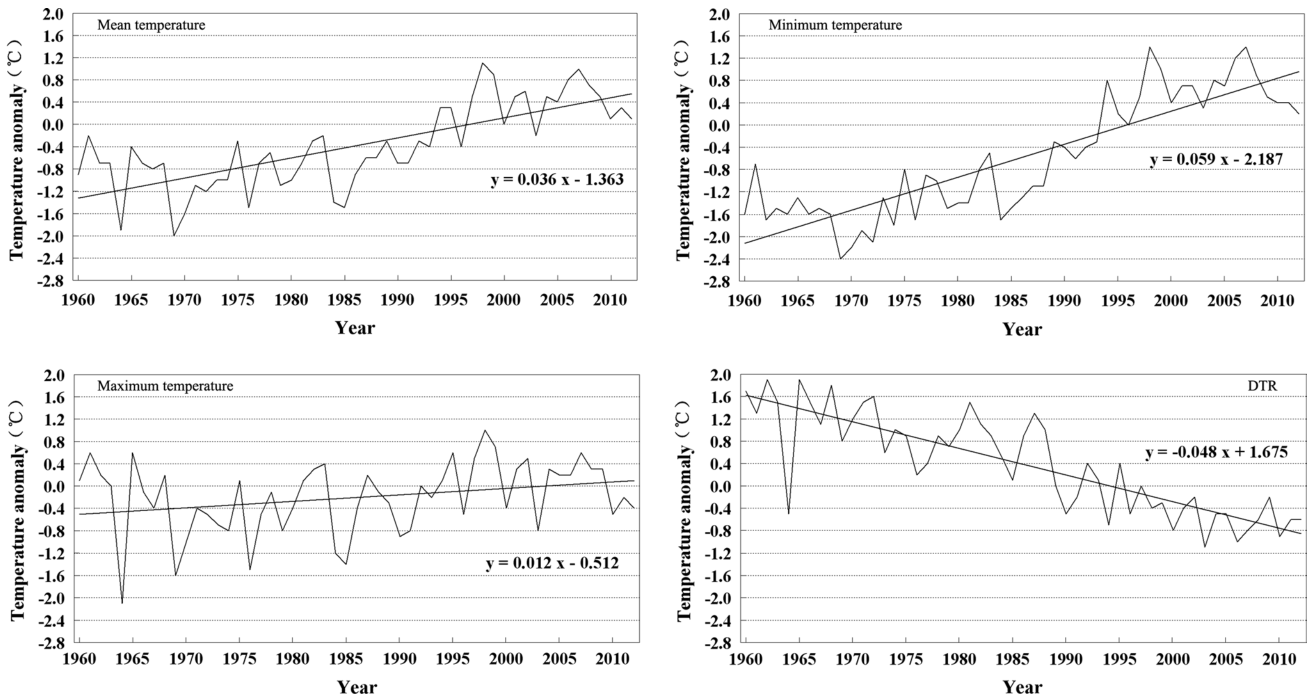

Fig. 2 Anomaly series of annual mean, minimum, maximum temperature, and the diurnal temperature range (DTR) at Shijiazhuang station during 1960–2012 (curved line) and their trends (straight line)

Table 2 Linear trends of annual and seasonal mean temperature at Shijiazhuang station during 1960–2012 (°C/decade)

	Mean temperature	Minimum temperature	Maximum temperature	DTR
Spring	0.39**	0.64**	0.16	− 0.48**
Summer	0.25**	0.41**	0.11	− 0.30**
Autumn	0.33**	0.53**	0.09	− 0.44**
Winter	0.45**	0.79**	0.10	− 0.69**
Annual	0.36**	0.59**	0.12*	− 0.48**

*Significant at $a = 0.05$ confidence level

**Significant at $a = 0.01$ confidence level

There were significant upward trends in the seasonal mean temperature in all four seasons, with linear trends of 0.39, 0.25, 0.33, and 0.45 °C/decade for spring, summer, autumn, and winter, respectively (Table 2). The strongest warming was found in winter. With the exception of November, the seasonal mean temperature in each month had a significant increasing trend (Fig. 3). The larger increase in winter mean temperature was consistent with the results reported in the previous studies (e.g., Ren et al. 2005; Bian and Lian 2008). The reasons for more rapid warming in winter might have been related to the weakening East Asian winter monsoon, a response to anthropogenic global warming, and the urbanization effect in the station over the past decades (Ren et al. 2005). The urbanization effect at the urban station would be examined in some details in the follows.

Figure 2 also shows that the annual mean minimum temperature at Shijiazhuang station in the last 53 years had a large and significant upward trend. The linear trend of 0.59 °C/decade was significant at the 0.01 level. The mean minimum temperature had a significant upward trend in all four seasons and for each month (Fig. 3), with the strongest warming in winter. In the last 53 years, the annual mean maximum temperature at Shijiazhuang station displayed a clear upward trend, with the linear trend of 0.12 °C/decade being significant at the 0.05 level. There were no significant long-term trends of the seasonal and monthly mean maximum temperature in the four seasons, with weak upward or downward trends in each month.

In the last 53 years, the annual mean DTR at Shijiazhuang station displayed a clear downward trend. The linear trend of − 0.48 °C/decade was significant at the 0.01 level. The seasonal mean DTR displayed a significant downward trend in all four seasons. The linear trends were − 0.48, − 0.30, − 0.44, and − 0.69 °C/decade in spring, summer, autumn, and winter, respectively (Table 2), with the strongest change in winter. There were also significant downward trends in the mean DTR of each month (Fig. 3).

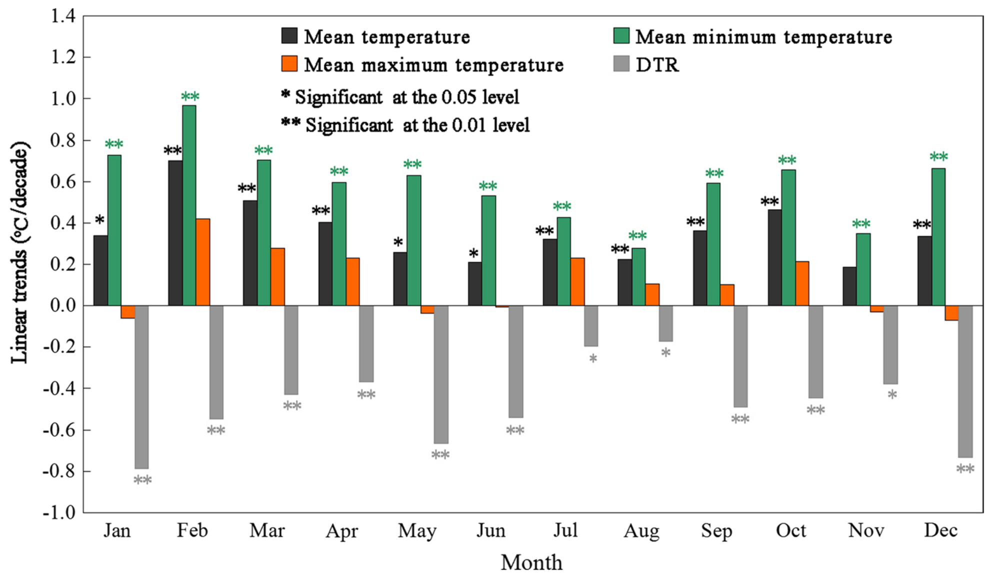

Fig. 3 Linear trends of monthly mean, minimum, maximum temperature, and DTR at Shijiazhuang station during 1960–2012

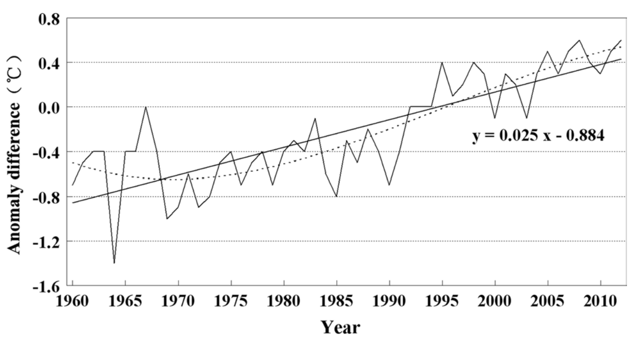

Fig. 4 Annual mean SAT anomaly differences between Shijiazhuang station and the rural stations during 1960–2012 (curved line), its linear trend (straight line), and the third-order polynomial curve (dotted line)

3.2 Urbanization effect on SAT trends

3.2.1 Mean temperature

Figure 4 shows the changes in the annual SAT anomaly differences between Shijiazhuang station and the rural stations in the last 53 years, and its linear trend and a third-order polynomial curve fitting. It can be seen that the annual SAT anomaly differences were negative before 1992, and mostly positive after 1992, when the increasing trend became obvious. In the last 53 years, the linear trend in the SAT anomaly differences was 0.25 °C/decade. Therefore, there was a significant urbanization effect on annual mean SAT series at Shijiazhuang station, with the urbanization contribution reaching 67.8% (Table 3). In the last 53 years, the urban–rural SAT anomaly difference was lowest (− 1.4 °C) in 1964 and highest (0.6 °C) in 2008 and 2012.

The third-order polynomial curve in Fig. 4 indicates that the urban–rural annual mean SAT anomaly differences between Shijiazhuang station and the rural stations had a

Table 3 Urbanization effects (°C/decade) and urbanization contributions (%) for the annual and seasonal mean SAT at Shijiazhuang station during 1960–2012

	Mean temperature		Minimum temperature		Maximum temperature		DTR	
	UE	UC	UE	UC	UE	UC	UE	UC
Spring	0.26**	67.9	0.52**	80.4	0.02	–	− 0.51**	100
Summer	0.24**	93.7	0.36**	88.6	0.04	–	− 0.33**	100
Autumn	0.27**	82.0	0.46**	85.9	− 0.05	–	− 0.50**	100
Winter	0.22**	47.6	0.53**	68.1	− 0.12	–	− 0.66**	96.5
Annual	0.25**	67.8	0.47**	78.6	− 0.03	–	− 0.50**	100

UE urbanization effect, *UC* urbanization contribution

*Significant at $a = 0.05$ confidence level

**Significant at $a = 0.01$ confidence level

Table 4 Differences of annual mean SAT anomalies between Shijiazhuang station and the rural stations for different decades during 1960–2012 (°C)

Period	Mean temperature	Minimum temperature	Maximum temperature	DTR
1960s	− 0.59	− 1.25	0.14	1.39
1970s	− 0.59	− 1.13	− 0.08	1.05
1980s	− 0.43	− 0.79	− 0.02	0.78
1990s	0.09	0.27	0.08	− 0.37
2000s	0.37	0.51	− 0.04	− 0.55
1966–1976	− 0.60	− 1.27	− 0.04	1.23

downward change during 1960–1966, with the lowest values being in 1968–1978, before a clear upward trend began, with a rapid rise in the early 1990s. The urbanization effect on annual mean SAT series at Shijiazhuang station was, therefore, the weakest during time period 1968–1978 and the strongest during the last two decades.

Table 4 gives the averages of the urban–rural annual mean SAT anomaly differences for different decades. The differences in the 1960s and 1970s were low (both − 0.59 °C), but began to increase after the 1980s, with the 1980s registering an increase by 0.16 °C compared to the 1960s and 1970s, and the 1990s by 0.52 °C compared to the 1980s. Although the urban–rural SAT anomaly differences also displayed an increasing trend after 2000, the rate of increase was slower than in the 1990s. It should also be noted that the urban–rural annual mean SAT anomaly differences were low from the beginning of "Cultural Revolution" (1966) to the beginning of "Reform and Opening" period (1978), well below − 0.40 °C for 11 consecutive years (1968–1978), with the lowest values in 1969–1974.

Figure 5 shows the urban warming at Shijiazhuang station for the four seasons. In the last 53 years, the seasonal mean urban warming at the urban station in spring was 0.26 °C/decade. The urbanization effect on the change of the spring mean temperature was very large, with an urbanization contribution of 67.9% (Table 3). The urban warming in summer was 0.24 °C/decade, and the urbanization contribution reached 93.7%. In autumn and winter, urbanization effects were 0.27 and 0.22 °C/decade, respectively, and the urbanization contribution were 82.0 and 47.6%, respectively. All the urban warming trends of the station in summer, autumn, and winter were significant at the 0.01 level.

A further examination showed that, with the exception of November and December, the linear trends of the urban–rural monthly mean SAT anomaly differences were statistically significant, indicating clear warming trends caused by urbanization (figure not shown here). The monthly urbanization effects were 0.19–0.40 °C/decade (significant at the 0.05 or 0.01 level) in January to October, with the urbanization contribution in August reaching 100%.

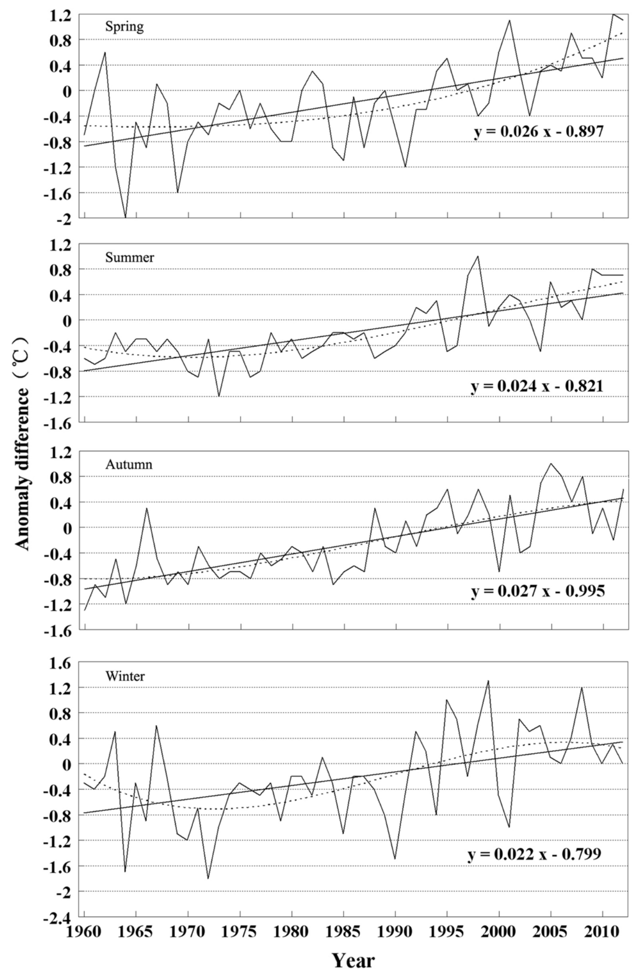

Fig. 5 Seasonal mean SAT anomaly differences between Shijiazhuang station and the rural stations during 1960–2012 (curved line), their linear trends (straight line), and the third-order polynomial curve (dotted line)

3.2.2 Minimum and maximum temperature

Figure 6 shows the changes in the annual mean minimum and maximum temperature anomaly differences between Shijiazhuang station and the rural stations in the last 53 years. The differences for minimum temperature were all negative before 1993, but exhibited an obvious upward trend after 1980. The differences were all positive after 1993, in spite of the fact that a slight decrease occurred after 2008. In the last 53 years, urbanization effect on annual mean minimum trend at Shijiazhuang station was 0.47 °C/decade, which was significant at the 0.01 level, and the urbanization contribution was 78.6% (Table 3). The urban–rural difference of annual mean minimum temperature was the lowest (− 1.7 °C) in 1972 and the highest (0.8 °C) in 2005 and 2007. It is also clear from Fig. 7 that an obviously weaker urbanization effect appeared during the time period 1964–1976 compared to the annual mean temperature.

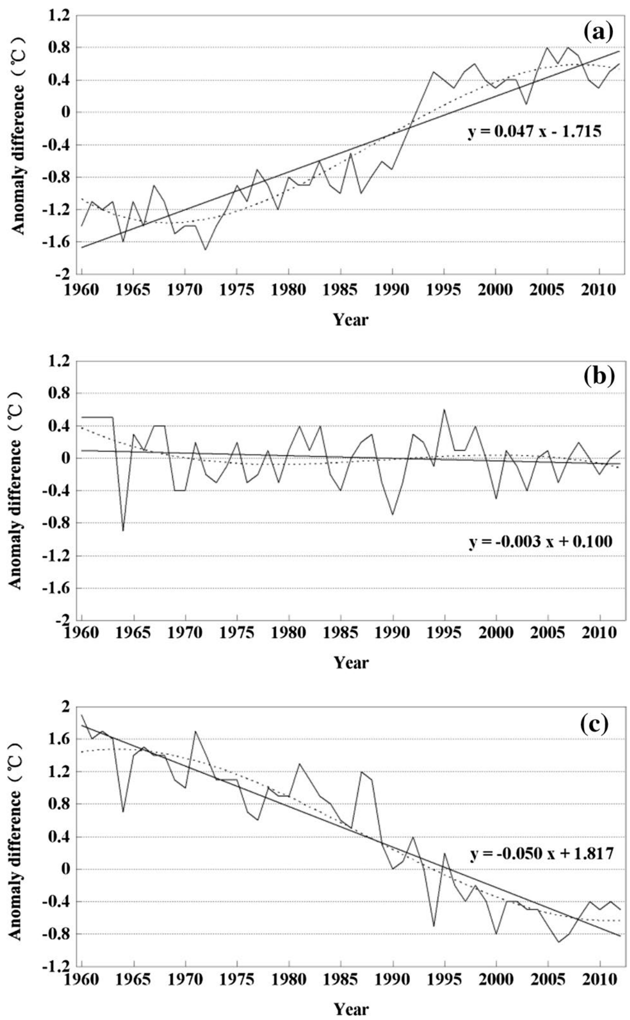

Fig. 6 Annual mean minimum temperature anomaly differences (**a**), annual mean maximum temperature anomaly differences (**b**), and annual mean DTR anomaly differences (**c**) between Shijiazhuang station and the rural stations during 1960–2012 (curved line), their linear trends (straight line), and the third-order polynomial curves (dotted line)

A most important aspect of UHI effect was the warmer nighttime and wintertime in northern China, leading to an increase in minimum temperature and winter mean temperature (Ren et al. 2008). The reasons for the asymmetric seasonal and diurnal variations might be related to formation mechanism of UHI in temperate zones of the world. The short-wave radiation from the sun was absorbed by the urban canopy, heating the ground surface and the buildings. The heat would be emitted to the low atmosphere as long-wave radiation, increasing the surface air temperature and making a higher minimum temperature. The effect would be more obvious due to the larger zenith angle of the sun. Heating in winter night and the increased heat release into the boundary layer would be also important for the larger UHI effect in areas of northern China like Shijiazhuang City.

Table 4 also gives the averages of the urban–rural annual mean minimum temperature anomaly differences for different decades. The differences in the 1960s and 1970s were both low (− 1.25 and − 1.13 °C, respectively), and the average for period 1966–1976 was as low as − 1.27 °C. Although the differences in the 1980s were negative (− 0.79 °C), an obvious increase can be seen, with the magnitude of increase being 0.34 °C compared to the 1970s. The largest decadal difference (0.51 °C) occurred in the 2000s, but it increased by only 0.24 °C compared to the 1990s.

All four seasons saw obvious upward trends of the mean minimum temperature anomaly differences (Fig. 7). The urbanization effects were 0.52, 0.36, 0.46, and 0.53 °C/decade in spring, summer, autumn, and winter, respectively, with all being significant at the 0.01 level. The urbanization effects on seasonal mean minimum temperature trends were stronger in winter and spring than in summer and autumn, and the urbanization contributions reached 80.4, 88.6, 85.9, and 68.1% in spring, summer, autumn, and winter, respectively.

The strongest urbanization effects on monthly mean minimum temperature series occurred in January and October, both reaching 0.58 °C/decade, with urbanization contributions of 79.9 and 88.6%, respectively. In February and May, the urbanization effect was 0.57 °C/decade and the urbanization contributions were 59.1 and 90.2%, respectively. August saw a relatively weak urbanization effect, but it was still significant at the 0.01 level, with the urbanization contribution being 99.4%. The urbanization effects on the minimum temperature trends of each month in the last 53 years were all significant at the 0.01 level.

Unlike the significant urbanization effect on annual mean minimum temperature trend, the linear trend of the annual mean maximum temperature anomaly difference between Shijiazhuang station and rural stations was not so evident (Fig. 6). It displayed only a slight downward trend of − 0.03 °C/decade, indicating that the urbanization effect on annual mean maximum temperature change at the urban station was quite weak. The urbanization effects in spring, summer, autumn, and winter were 0.02, 0.04, − 0.05, and − 0.12 °C/decade, respectively, none of which were statistically significant. It is also obvious that, in comparison with the more significant warming trend of the annual mean minimum temperature than that of the annual mean maximum temperature, the urbanization effects on annual mean minimum and maximum temperature trends were even more asymmetrical.

3.2.3 Annual and seasonal mean DTR

Figure 6 also shows the changes in the annual mean DTR anomaly differences between Shijiazhuang station and the rural stations in the last 53 years. All the differences were

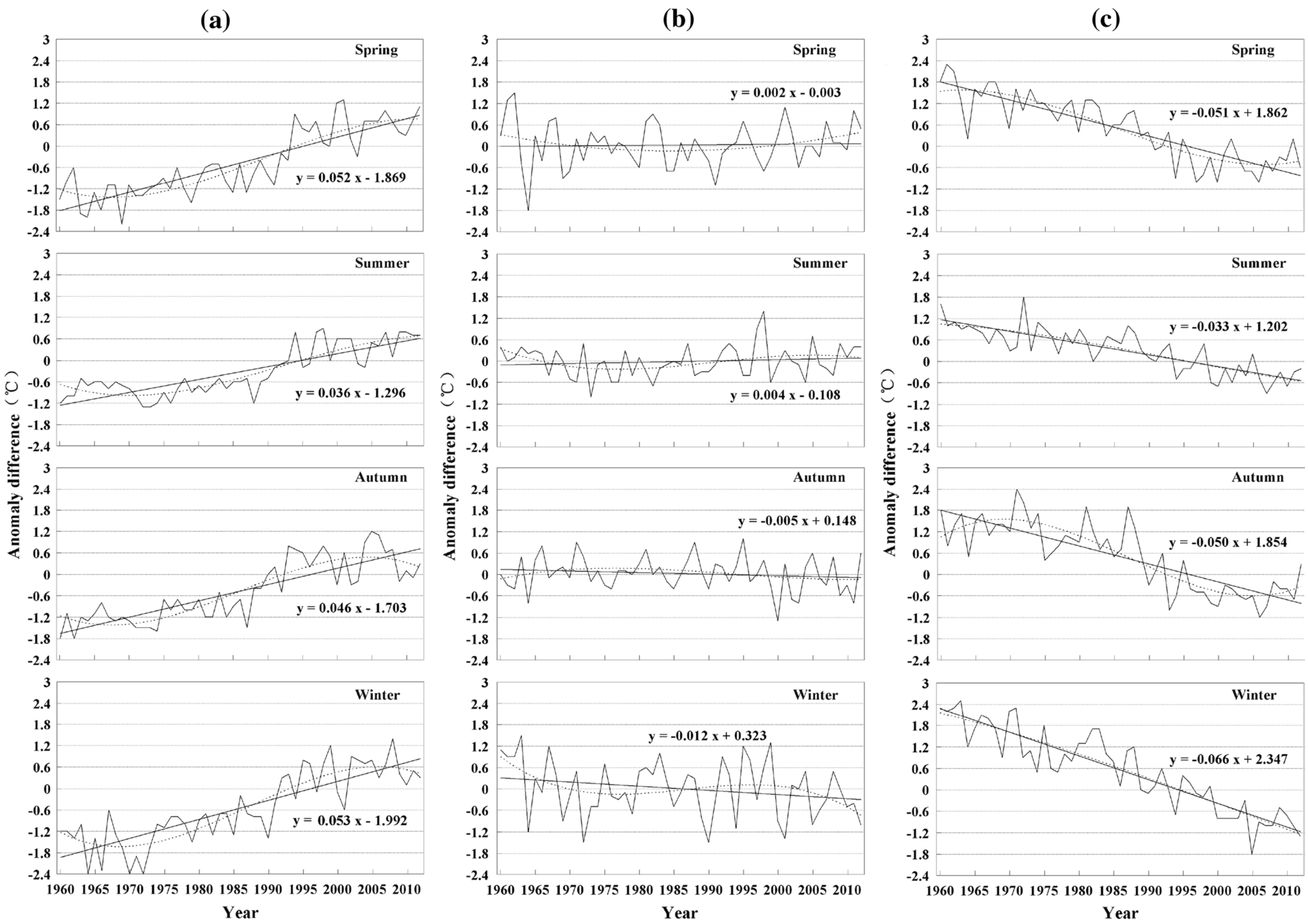

Fig. 7 Seasonal mean minimum temperature anomaly differences (**a**), seasonal mean maximum temperature anomaly differences (**b**), and seasonal mean DTR anomaly differences (**c**) between Shijiazhuang station and the rural stations during 1960–2012 (curved line), their linear trends (straight line) and the third-order polynomial curve (dotted line)

positive before 1993, with the highest value (1.9 °C) in 1960, and all those after 1993 were negative, with the lowest value (− 0.9 °C) in 2006. The 1993 shift point might be related to the expansion of the built-up areas to the surrounding zone of the observational site around the mid-1990s. In the entire period analyzed, an urbanization effect of − 0.50 °C/decade at Shijiazhuang station was significant at the 0.01 level, with the urbanization contribution reaching 100%, implying that the decline of annual mean DTR was completely caused by urbanization. It was worth noting that the four-station averaged annual mean DTR series actually showed a slight upward trend rather than a decreasing trend over the whole time period, leading to an urbanization contribution of over 100%. According to the definition of this paper, however, the over 100% contribution was regarded as 100%. The third-order polynomial curve of the urban–rural differences in Fig. 6 showed no obvious changes during 1960–1976, but a large downward trend after 1976.

The averages of the urban–rural annual mean DTR anomaly differences for different decades are indicated in Table 4. The 1960s witnessed the highest average (1.39 °C), and there was a continuous decrease thereafter, with the 1970s being 0.34 °C lower than the 1960s, 1980s 0.27 °C lower than the 1970s, and the 1990s 1.15 °C lower than the 1980s. The lowest value (− 0.55 °C) was observed in the 2000s, though the rate of decline slowed. It is also worth noting that the high value of the annual mean DTR anomaly differences (1.23 °C) was registered in 1966–1976. Therefore, the urbanization had led to a continuous and tremendous decline in annual mean DTR of Shijiazhuang station, and this could be seen especially clearly after the mid-1980s (Fig. 6 and Table 4).

The urbanization effects on seasonal mean DTR changes at Shijiazhuang station in the last 53 years were large and significant for all the seasons (Fig. 7 and Table 3). They were − 0.51, − 0.33, − 0.50, and − 0.66 °C/decade in spring, summer, autumn, and winter, respectively, with the urbanization contributions reaching as high as 100, 100, 100, and 96.5%, respectively, indicating that the decrease of seasonal mean DTR for spring, summer, and autumn was totally induced by urbanization and that for winter was almost completely caused by the urbanization.

Urbanization effects on monthly mean DTR trends at Shijiazhuang station were significant at the 0.01 level for all the months (figure not show here). The largest urbanization effect, − 0.78 °C/decade, was in January, with an urbanization contribution of 98.5%. The second largest urbanization effects occurred in May and December (both − 0.64 °C/decade), with urbanization contributions of 95.3 and 87.9%, respectively. August witnessed the smallest urbanization effect (− 0.23 °C/decade), but it was still significant, and the urbanization contribution reached 100%.

4 Discussion

There have been many analyses of the effects of urbanization on the changing trends of SAT series at single stations or regions, including at Shijiazhuang station. The estimated values of the urbanization effects obtained from the studies, some of which applied data without any adjustments for inhomogeneities or data from non-rural stations as reference series, are relatively conservative and the actual urbanization effects should be larger (Ren et al. 2008, 2015). Bian et al. (2012) concluded that the increasing trend of the annual mean SAT due to the increase in UHI intensity during 1962–2009 at Shijiazhuang station was 0.19 °C/decade, whereas the urbanization effect obtained in this study was 0.25 °C/decade during 1960–2012 for the same station, approximately 0.06 °C/decade higher than the previous analysis. This difference may have not been explained by the data inhomogeneities or the varied lengths of data series used. Rather, it may have been related to the usage of the different reference stations.

To examine the possible impact of different reference series on analysis results, we re-calculated the urbanization effects on SAT trends of Shijiazhuang station for the same time period as used in this paper, applying the reference stations used Bian et al. (2012, 2015). The early version of reference station data were from Gaocheng (no. 53697), Yuanshi (no. 53791), Pingshan (no. 53694), and Xinle (no. 53695), and the details of the stations are also given in Table 1. These stations are more close to Shijiazhuang station, with the furthest distance being less than 90 km, and the largest elevation differences less than 80 m (see Table 1 in Bian et al. 2015).

Figure 8 shows the comparison of annual, seasonal, and monthly mean urbanization effects at Shijiazhuang station during 1960–2012 when different data of reference stations were selected. A marked difference in the urbanization effects can be found. In all of the months, the values obtained in this paper are larger than those in the previous work, with the differences for spring, summer, and autumn more remarkable. The old reference stations around Shijiazhuang station are all located in towns or even small cities, and the observational records of surface air temperature may be still affected by urban development in a certain extent. This was ever pointed out in the previous paper indicating that the urbanization effects calculated should be regarded as the lowest estimates (Bian et al. 2015). Therefore, the results given in this study are more robust, because the reference stations used are more representative than those used before.

It is obvious from Fig. 8 that the urbanization effect on the long-term trend of annual and seasonal mean temperature is larger than our previous study (Bian et al. 2015). It is 0.25 vs. 0.19 in terms of annual mean temperature, and this difference is significant considering the relatively small variability of annual mean temperature. The cause for the difference is the usage of more representative rural stations in this analysis. Although the difference is not so large as compared to the overall change in temperature, it shows that the earlier studies including that by ourselves for Shijiazhuang station underestimated the urbanization effects on site and bulk observations. This problem was also realized in a few

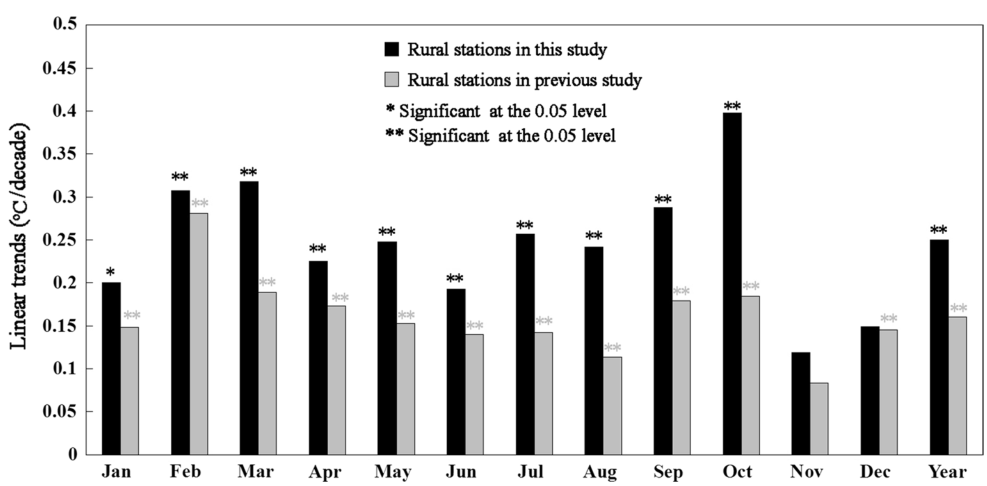

Fig. 8 Comparison of the annual, seasonal and monthly urbanization effects at Shijiazhuang during 1960–2012 when different data of reference stations were applied

of the previous other studies (e.g., Ren et al. 2005, 2015; Ren and Zhou 2014). In evaluating the urbanization effect on annual surface air temperature trends of the national stations of North China and mainland China on a whole over the last half a century, Ren et al. (2008, 2015) pointed out that the results should be regarded as the lowest estimates due to the non-representative reference stations used in the studies. One worrisome problem is that the four rural stations as used in this study are not located in real rural sites as well, and they could not represent the regionally background change in surface air temperature. Therefore, it is safe to mention that the urbanization effect and contribution reported in this paper are still conservative. Because there are many similar urban stations included in the current global and regional land surface air temperature data sets, our analysis in this paper further indicates the importance and urgency for climatological community to pay more attention to the urbanization effect in the current global and regional data sets.

Asymmetric trends in SAT series were reported in the previous studies. Karl et al. (1993) indicated that an asymmetric variation of minimum and maximum temperature was widespread across the world, which had led to a decrease in the DTR. Xie and Ca (1996), Zhai and Ren (1997), Dai et al. (1999) and Chen et al. (2005), among others, confirmed the asymmetric variation of the SAT in mainland China. The rise in the minimum temperature is also bigger than that of the maximum temperature at Shijiazhuang station, leading to a significant decrease in the DTR (Bian and Lian 2008). However, there are different interpretations of the reasons for this asymmetric variation of temperature and the subsequent decrease in DTR (Ren and Zhou 2014). Some analyses related the DTR decline to change in vapor content and cloud coverage in northern China, which were considered as a response to the global climate warming (e.g., Dai et al. 1999). However, the atmospheric vapor content and cloud coverage generally decreased over the last decades in northern China, and they were impossible to cause DTR drop at Shijiazhuang station (Zhou and Ren 2009; Ren and Zhou 2014). Large-scale land use and land cover change and the increasing aerosols emission were regarded as dominant factors for the DTR decrease (e.g., Huang et al. 2006; Wang et al. 2012; Wu and Zhang 2013). The aerosols were more evenly distributed across the whole northern China, and the reference stations in the region did not see the significant DTR drop (Zhou and Ren 2009), implying that they might not a major factor for the large decrease of DTR at Shijiazhuang station. As for the possible influence from the large-scale land use and land cover change in the region, there were few observational studies, and further investigation is needed.

The results of this study showed that the SAT at Shijiazhuang station had also displayed an asymmetric trend since 1960, with the increase in the minimum temperature being considerably greater than that of the maximum temperature and the tremendous decrease in DTR. It was apparent, however, that the urbanization effect on the SAT had an obvious asymmetry, with the mean minimum temperature series witnessing much larger urbanization effect than the mean maximum temperature. The urbanization effect on the DTR series was large and significant, almost explaining the overall decrease of DTR at the urban station. It was beyond doubt to say, therefore, that the asymmetric trend of the SAT and the large decline of DTR at the urban station are due mainly to the urbanization effect. This is consistent with a few previous works by Chen et al. (2005), Ren et al. (2008) and Zhang et al. (2014), who all reported a significant urbanization effects on the asymmetric change of SAT and a decreasing trend of DTR for urban stations and the national stations in areas and mainland China on a whole over the last decades. We used only one urban station in this analysis, and this might not explain the real reasons of DTR change in a larger region like North China. However, our results did indicate the dominant role of the urbanization in the decline of the DTR at the urban station. It was possible that aerosols would also be important in driving the DTR change due to the higher concentration in the city, but the increasing aerosols themselves were also a part of urbanization over the past decades.

This study also confirmed a recent finding that the urbanization effect was non-linear, with a relatively weak magnitude during the so-called "Cultural Revolution" of 1966–1976 in mainland China in North China (Ren and Zhou 2014). We found that the annual urbanization effects on the mean SAT (annual and winter), minimum temperature (all four seasons), and mean DTR (mostly obvious for annual, spring, and autumn mean DTR) were the weakest during 1966–1978 at Shijiazhuang station. The minimum urbanization effects during the "Cultural Revolution" might be related in some extents to the de-urbanization process characterized by the movement of urban dwellers to villages. It is also worth noting that the UHI intensity near Shijiazhuang station was relatively weak before the 1980s due to the suburban location at that time, and any signal of the "Cultural Revolution" in the temperature series would have been more obvious if the station was within the built-up areas of the city. Qian (2016) recently also noted the non-linear change of urbanization effect in the hot extreme index series of Shanghai station.

The urbanization effects on the trends of annual and seasonal mean SAT, minimum temperature and DTR at Shijiazhuang station all began to increase after the mid-1990s. This may have been resulted from an accelerated urbanization after the late 1980s and the early 1990s, characterized by a rapid urban population growth. The population of the city exceeded 1 million in 1980, with a growth rate of 288,000/decade during 1981–1990, 332,000/decade during 1991–2000, and 855,000/decade during 2001–2012. The urban population exceeded 2 million in 2002 and was already close to 3 million in 2012. The urban area began to expand significantly during 1977–1990, increasing by 55% compared to 1965, and it doubled during 1990–1996. Therefore, the enhancement of the urbanization effect in the temperature series at the urban station is closely related to the rapid development of the city over the last three decades.

In addition to the non-representative reference stations, the residual uncertainties in the estimates of urbanization effect may come from the impact of serial correlation of the urban–rural temperature anomaly difference series on the linear trend values and significance levels. Despite there is a debate on this issue (Yue and Wang 2002; Zhang and Zwiers 2004; Bayazit and Onoz 2007), we compared the estimates of urbanization effects and their significance levels between the urban–rural temperature anomaly difference series with and without serial correlations, by referring to the method of Wang and Swail (2001). The result shows that the differences are generally small, and they usually less than 0.03 °C/decade in terms of urbanization effect. For example, the trend of the original temperature difference series is 0.25 °C/decade, and the trend of the temperature difference series without series correlation is 0.24 °C/decade; the urbanization effect in the original annual DTR dereference series is − 0.50 °C/decade and that in the annual DTR dereference series without serial correlation is − 0.52 °C/decade. However, the significance level of the trend estimates is generally lower than those made based on the original temperature/DTR difference series. The upward trend in the original annual mean temperature difference series is significant at the 0.01 significance level, but it is significant only at the 0.05 significance level when serial correlation is removed, confirming the previous claim that the autocorrelation will probably affect the uncertainty interval of the trend estimated, but will not significantly affect the best estimate of the trend (Zhang et al. 2000; Wang and Swail 2001; Zhang and Zwiers 2004; Qian 2016).

Overall, the series correlation impact on the estimates of linear trends and significance levels in this work is small and has not significantly affected the analysis results. However, this issue should be paid more attention in the similar analyses.

5 Conclusions

Based on updated SAT data from Shijiazhuang station and a set of new reference stations selected based on an objective method, a reanalysis of the urbanization effect on the SAT changes at the urban station in the last 53 years was undertaken with the following conclusions:

1. The urbanization effect on annual mean SAT trends was 0.25 °C/decade, which was significant at the 0.01 level, with an urbanization contribution of 67.8%. The urbanization effects on the mean SAT in all four seasons were significant, with the urban warming reaching 0.26, 0.24, 0.27, and 0.22 °C/decade and the urbanization contributions 67.9, 93.7, 82.0, and 47.6% in spring, summer, autumn, and winter, respectively. With the exception of November and December, the urbanization effects on the monthly mean SAT trends in all months were significant.
2. The urbanization effect on annual mean minimum SAT was 0.47 °C/decade, which was significant at the 0.01 level, with an urbanization contribution of 78.6%. The urbanization effects on the seasonal mean minimum SAT were 0.52, 0.36, 0.46, and 0.53 °C/decade and the urbanization contributions were 80.4, 88.6, 85.9, and 68.1% in spring, summer, autumn, and winter, respectively. However, the urbanization effects on the annual and seasonal mean maximum SAT trends were much weaker.
3. The annual and seasonal mean DTR series all witnessed significant urbanization effects, with the annual mean effect reaching − 0.50 °C/decade and annual urbanization contribution 100%. The urbanization effects on the seasonal mean DTR trends were − 0.51, − 0.33, − 0.50, and − 0.66 °C/decade for spring, summer, autumn, and winter, respectively, and the urbanization contributions were 100% except for winter.
4. The updated analysis evidenced that our previous work for the station had underestimated the urbanization effect and its contribution to the overall changes in the SAT series. It also implied that more attention had to be given to the urbanization bias in the monitoring and detection of global and regional SAT change, because many similar urban stations were being included in the current national and regional SAT data set.

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