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Tao Bian, Guoyu Ren & Yanxia Yue

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NOTES AND COMMENTS

Effect of Urbanization on Land-Surface Temperature at an Urban Climate Station in North China

Tao Bian[1,2] · **Guoyu Ren**[1,3] · **Yanxia Yue**[2]

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Abstract While the land-surface temperature (LST) observed at meteorological stations has significantly increased over the previous few decades, it is still unclear to what extent urbanization has affected these positive trends. Based on the LST data recorded at an urban station in Shijiazhuang in North China, and two rural meteorological stations, the effect of urbanization at the Shijiazhuang station for the period 1965–2012 is examined. We find, (1) a statistically-significant linear trend in annual mean urban–rural LST difference of 0.27 °C (10 year)$^{-1}$, with an urbanization contribution of 100% indicating that the increase in the annual mean LST at the urban station is entirely caused by urbanization. The urbanization effects in spring, summer and autumn on the trends of mean LST are also significant; (2) the urbanization effect is small for time series of the annual mean minimum LST, and statistically marginal for the trend in annual mean maximum LST [0.19 °C (10 year)$^{-1}$]; (3) the urbanization effect on the annual mean diurnal LST range (ΔLST) at the urban station is a strongly significant trend of 0.23 °C (10 year)$^{-1}$, with an urbanization contribution of 21%. The urbanization effects on trends in the spring and autumn mean ΔLST are also larger and more significant than for the other seasons; (4) the urbanization effects on the long-term LST trends are remarkably different from those on the near-surface air temperature at the same urban station. Nonetheless, the significant warming of the urban boundary layer is expected to affect the urban environment and ecosystems. However, the problem of data representativeness at an urban station for the monitoring and investigation of large-scale climate change remains.

✉ Guoyu Ren
guoyoo@cma.gov.cn

[1] Department of Atmospheric Science, School of Environmental Studies, China University of Geosciences, Wuhan 430074, China

[2] Shijiazhuang Meteorological Bureau, Shijiazhuang 050081, China

[3] Laboratory for Climate Studies, National Climate Center, China Meteorological Administration (CMA), Beijing 100081, China

Keywords Climate change · Land-surface temperature · North China · Urbanization effect · Urbanization contribution

1 Introduction

Land-surface processes affect weather and climate through the underlying surface reflectance, soil moisture, and soil heat storage (Tang et al. 1982; Pouyat et al. 2007). The land-surface temperature (LST) of the Earth determines the extent of frozen soil and the near-surface atmospheric heat balance. Studies have been conducted on the spatial and temporal patterns of the LST in mainland China and other regions of the world, and the analyses of the relationships between regional LST variation and climate change have also been reported for many regions (e.g. Mareschal and Beltrami 1992; Baker and Ruschy 1993; Harris and Chapman 1997; Bodri and Cermfik 1998; Li et al. 2005; Jian et al. 2006; Zhuo et al. 2009; Wang et al. 2009; Lin and Li 2011). By collecting and analyzing LST data in the permafrost region of northern Alaska, USA, Lachenbruch and Marehall (1986) revealed a 2–4 °C increase in LST per decade of the previous century. Lu et al. (2006) analyzed the changing characteristics of LST in different regions of mainland China using monthly mean LST data from 532 stations during the period 1954–2001 and found little change in the inter-decadal variation in the nationwide-average annual mean LST, though a significant upward trend over the entire period was detected. Wang et al. (2009) analyzed the long-term LST change in the city of Nanjing in eastern China, and showed a significant increase during the previous 30 years. Lin and Li (2011) showed that the annual mean LST in the Shiyang River Basin of north-western China experienced a significant increase, especially after the mid-1980s. Zhang et al. (2012, 2013a, b) analyzed the variation of LST at Shijiazhuang station, and reported a warming trend in the annual mean LST and annual mean minimum LST, but a negative trend in annual mean maximum LST, during the period 1961–2010. Overall, the previous studies for mainland China generally show long-term increasing trends in annual and seasonal mean LST for the previous 40–60 years in a few regions.

Urbanization has an obvious impact on the surface environment (Brazel et al. 2000), whereby the natural vegetation in humid regions at mid-latitudes has been mostly transformed into urban and agricultural land. The replacement of grass and forest with cement and asphalt in urban areas has greatly changed the natural cycle of material and energy, and modified regional climate and ecosystems (Pataki et al. 2006; Pouyat et al. 2007). Examination of the urbanization effect on the change in surface-air temperature has found significant urban warming based on data recorded at Chinese meteorological stations during the previous four to six decades (e.g. Chu and Ren 2005; Chen et al. 2005; Ren et al. 2008, 2014, 2010; Guo et al. 2009; Zhang et al. 2010; Bian et al. 2012). Zhang et al. (2010) showed that urbanization during 1961–2004 contributed more than 27% of the overall increase in annual mean surface-air temperature averaged over mainland China based on data from the national reference climatic stations, as well as basic meteorological stations. Bian et al. (2012) found that the annual mean urban warming due to urbanization around the Shijiazhuang station during 1962–2009 is 0.19 °C (10 year)$^{-1}$, with urbanization contributing 68% to the overall warming trend.

Comprehensive investigations into the effect of urbanization on LST trends have been lacking so far. Using both meteorological and remote sensing data, Cao et al. (2010) analyzed the effect of urbanization on the temporal and spatial pattern of LST in Beijing City for three different periods with varied levels of urbanization. By analyzing the difference between urban–rural shallow soil temperatures, Shi et al. (2012) found a significant urban heat island (UHI) in Nanjing City, with the annual mean soil temperature of an urban station being 2 °C higher than those at suburban sites. It is unclear, however, whether significant urban warming exists in the long-term LST data and/or soil temperature data of the urban meteorological stations in mainland China, as frequently reported for the surface-air temperature.

Based on LST data at the urban Shijiazhuang station and two rural stations during 1965–2012, we examine the nature and magnitude of urbanization effects on the long-term trends in LST time series at the urban station. Our results offer a reference for studies on the detection of regional climate change, surface–atmospheric processes, and the urban planning and environmental management of Shijiazhuang.

2 Data and Methods

The LST is analyzed here as it has been frequently applied in investigations of long-term changes in the near-surface climate, with a change of temperature different from that found for surface-air temperature data. The LST is also important for understanding the interaction between the land and flow in the boundary layer. While the LST data include the ground surface temperature of the bare soil, grass and snow, including the daily mean temperature, as well as the maximum and minimum temperatures, the ground surface temperature of bare soil is examined here.

At the meteorological stations of mainland China, a glass liquid thermometer and the platinum resistance temperature sensor are used to measure the LST. The structure and principles of the ground thermometer (also called the 0-m thermometer) are the same as that for recording the 2-m air temperature. According to the Standard of Surface Meteorological Observation issued by the China Meteorological Administration (2003), a 2-m wide by 4-m long observational area for ground temperature measurement is to be located in the southern part of an observational flat and bare surface. The LST is observed and recorded at 0200, 0800, 1400 and 2000 Beijing local time (BLT), and ground thermometers measure the maximum and minimum temperature at 2000 BLT; observations are recorded manually while the ground thermometer makes contact with the ground.

Since 2004, automatic observations of the ground temperature have been carried out. Because of the different specifications between the automatic and manual observations, the automatic weather station detects generally higher temperatures than the manual station during snow cover in winter. However, as these days at Shijiazhuang are rare, errors due to the snow cover are ignored. The data of daily maximum, minimum, and mean LST at the Shijiazhuang, Gaocheng and Yuanshi meteorological stations during 1965–2012 are considered (Fig. 1; Table 1), with data being quality controlled by the Shijiazhuang Meteorological Bureau; any incorrect records caused by artificial factors have also been corrected.

The two rural stations were relocated multiple times during the study period; Gaocheng station twice and the Yuanshi station three times. However, since a preliminary check of the annual mean LST anomaly series at the two stations yielded no significant breakpoints near the relocation dates, data from the two stations are regarded as relatively homogeneous. Moreover, the use of two rural stations rather than one station to construct the reference LST series reduces the impact of any possible inhomogeneities resulting from relocations and different instrumentation.

Four seasons are defined as follows: spring (March, April, May), summer (June, July, August), autumn (September, October, November), and winter (December, January, Febru-

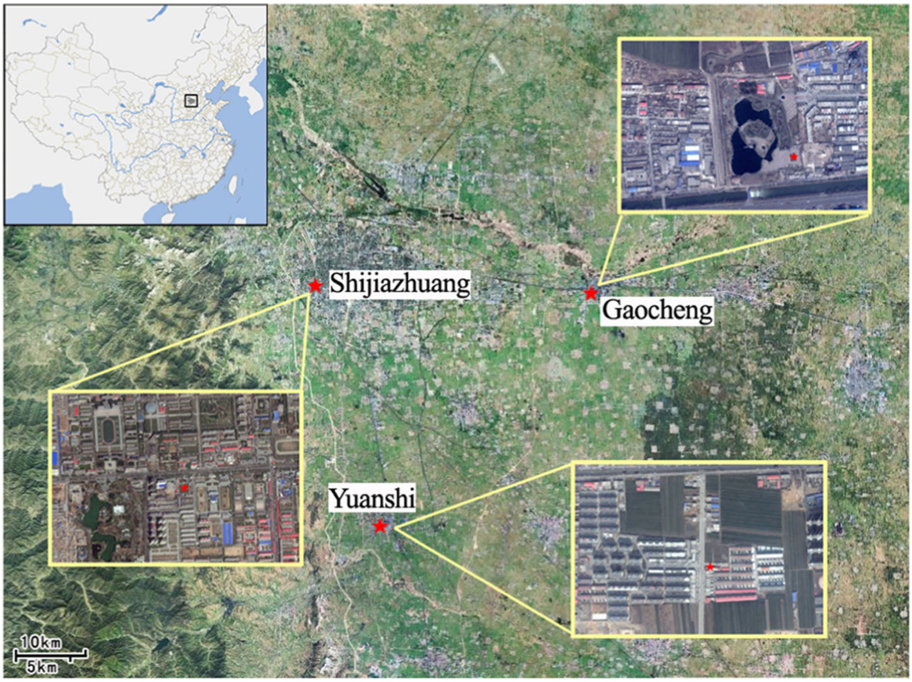

Fig. 1 Locations of the three meteorological stations. Detailed information of the three stations is shown in Table 1

ary). For example, the data for winter 1965 are records from December 1964 to February 1965. The monthly and seasonal mean LST are calculated based on daily readings, with the annual mean LST calculated from the monthly mean LST.

A significant influence of the UHI effect on the surface-air temperature at Shijiazhuang station, which is a typical urban station, was previously reported by Bian et al. (2012). As the urban station was only relocated to a rural site on 31 December 2012, continuous records before 1 January 2013 serve as an indicator of urban climate change. The Gaocheng and Yuanshi stations are situated in relatively rural areas (Fig. 1) more than 10 km from the central urban areas, though they were actually established near two towns with urban populations of about 0.1 million. The two rural stations have an average altitude of 60 m, which is close to the altitude of the urban station (81 m). As economic growth has been relatively slow, urbanization is lower in the two towns. The two rural stations have previously been used as the reference stations for analyses of the urbanization effect on LST change (Bian et al. 2012, 2015), and have been shown to be representative of the relatively rural sites. No nearby station with the corresponding record lengths in truly rural areas is available.

The LST trends are obtained from the linear regression relation,

$$xi = a + bt_i \tag{1}$$

for $i = 1, 2, 3, \ldots, n$, where a and b are the regression coefficients, with $10b$ regarded as the linear trend or change in the LST in units of °C (10 year)$^{-1}$ (Wei 2007). The values of a and b are estimated using the least-squares method. The correlation coefficients for the LST time series are also calculated to verify the nature and magnitudes of the trends, the significance of which are assessed using a Student's t-test.

Table 1 Information of the three meteorological stations used in this study; a.s.l. is above sea level (m)

Station		Longitude (E)	Latitude (N)	Altitude (a.s.l.) (m)	Start time	Time of relocation	Population (million)
Urban station	Shijiazhuang	114.42°	38.03°	81.0	1 December 1954	1 January 2013	2.7
Rural station	Gaocheng	114.81°	38.01°	53.5	1 August 1958	14 July 1969 1 January 1999	0.1
	Yuanshi	114.53°	37.75°	66.4	1 January 1960	17 February 1982 1 January 1998 1 January 2007	0.08
	Mean of rural stations	114.67°	37.88°	60.0	~	~	0.09

Temperature anomalies are calculated relative to the base period 1981–2010. To more clearly discriminate the different trends of the urban and rural LST anomaly series, the first-year anomaly difference between the urban and rural LST anomaly series is calculated, and then subtracted from the annual LST anomalies of the rural stations to force the first year of the two series to share the same value. In addition, the following terms are defined with reference to Chu and Ren (2005), Ren and Zhou (2014) and Bian et al. (2015):

Urbanization effect: the linear trend in LST at the urban station, caused by an increase in the intensity of the UHI effect and/or other locally-induced anthropogenic factors, is expressed as

$$\Delta T_{u-r} = T_u - T_r, \tag{2}$$

where T_u is the linear trend of the LST series at the urban station, and T_r is the linear trend of the average LST series at the rural stations.

If $\Delta T_{u-r} > 0$ ($\Delta T_{u-r} < 0$), the LST series at the urban station has a positive (negative) trend in relation to that of the rural stations due to the urbanization effect. The linear trend in time series of the LST difference between the urban and rural stations is another expression of the urbanization effect equal to ΔT_{u-r}. The correlation coefficients of time series of the LST anomaly difference are used to determine the statistical significance of the urbanization effect.

Urbanization contribution: the proportion of the statistically-significant urbanization effects to the overall trend of the LST series at the urban station is expressed as

$$C_u = |\Delta T_{u-r}/T_u|, \tag{3}$$

and because the urbanization effect is negative in certain circumstances, an absolute value is 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 LST series at the urban station. If $C_u = 100\%$, the linear trend of the LST series at the urban station is caused entirely by the urbanization effect. In practical calculations, C_u occasionally exceeds 100% when the trend of the urban station is positive and significant, and the trend of the rural stations is negative. This condition usually implies that unknown local anthropogenic or natural factors affect the temperature of urban or rural stations, so that C_u is manually set to 100%. As the definition implies, the urbanization contribution is not calculated if the urbanization effect is statistically insignificant.

Further details on the method used for quantifying the urbanization effect and urbanization contribution can be found in, e.g., Chu and Ren (2005), Ren et al. (2008, 2014), Zhang et al. (2010) and Bian et al. (2015).

3 Results

3.1 Changes in Urban and Rural LST

Figure 2 shows changes in the annual mean urban and rural LST anomalies and their linear trends at the Shijiazhuang station during 1965–2012, where a positive trend of 0.13 °C (10 year)$^{-1}$ in the annual mean LST at the urban station is seen, which is significant at the 0.05 level. In contrast, a downward trend of −0.14 °C (10 year)$^{-1}$ in the annual mean LST at the rural stations is detected, which is also significant at the 0.05 level. Among the four seasons, only the winter mean LST at the urban station exhibits a significant positive trend of 0.31 °C (10 year)$^{-1}$ (Table 2), and the seasonal mean LST for the other three seasons shows insignificant changes, with the summer even showing a weak downward trend.

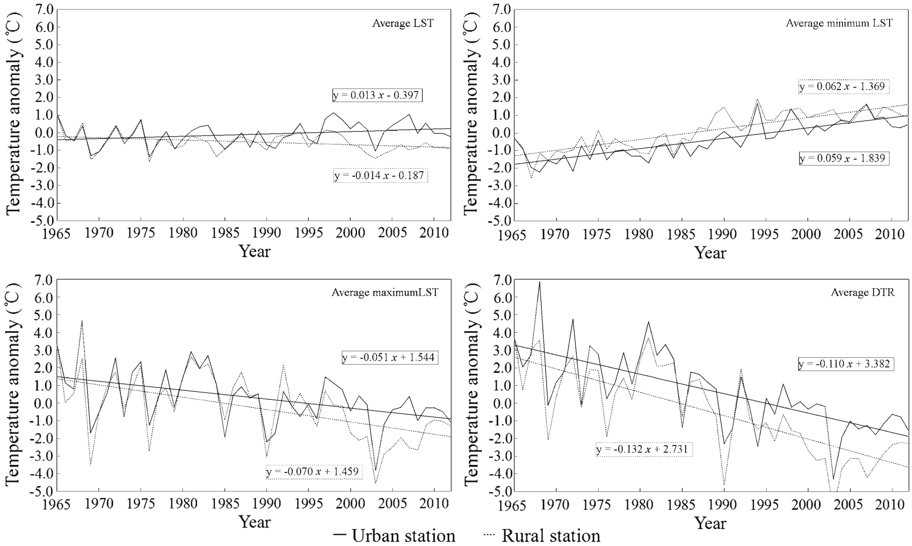

Fig. 2 Anomaly series and linear trends of annual mean, minimum, and maximum LST and the diurnal LST range (ΔLST) at the Shijiazhuang urban and rural stations during 1965–2012. The *black line* indicates the urban station, and *grey line* indicates the rural stations

Table 2 Linear trends of annual and seasonal mean, minimum and maximum LST in °C (10 year)$^{-1}$, as well as ΔLST at the urban and rural stations during 1965–2012

	Mean LST		Mean minimum LST		Mean maximum LST		Mean ΔLST	
	Urban	Rural	Urban	Rural	Urban	Rural	Urban	Rural
Spring	0.21	<u>−0.20</u>	0.60***	0.64***	−0.27	<u>−0.52</u>	−0.87***	−1.16***
Summer	−0.04	−0.53***	0.46***	0.49***	−0.67*	−0.90**	−1.13***	−1.38***
Autumn	0.04	−0.09	0.50***	0.58***	−0.68**	−0.83***	−1.17***	−1.43***
Winter	0.31***	0.27***	0.78***	0.75***	−0.37	−0.53*	−1.14***	−1.30***
Year	0.13*	−0.14*	0.59***	0.62***	−0.51***	−0.70***	−1.10***	−1.32***

Note (_) Denotes significance at the 0.10 level; * significant at the 0.05 level; ** significant at the 0.01 level; *** significant at the 0.001 level

The seasonal mean LST in spring, summer and autumn at the rural stations exhibits clearly decreasing trends. The negative trends of −0.20 and −0.53 °C (10 year)$^{-1}$ are observed for spring and summer, respectively, with the decrease in summer stronger and statistically significant at the 0.001 level. The positive trend in winter is 0.27 °C (10 year)$^{-1}$, which is significant at the 0.001 level.

The monthly mean LST for 3 months (February/March/April) at the urban station shows a significant positive trend, with the strongest warming in February (significant at the 0.001 level), whereas the monthly mean LST for the other nine months displays weak and insignificant changes (Fig. 3). The monthly mean LST in February, March and December at the rural stations has a significant positive trend, whereas negative trends are observed from May to September, with the strongest negative trends in May and June (both significant at the 0.001 level); changes for other months are insignificant.

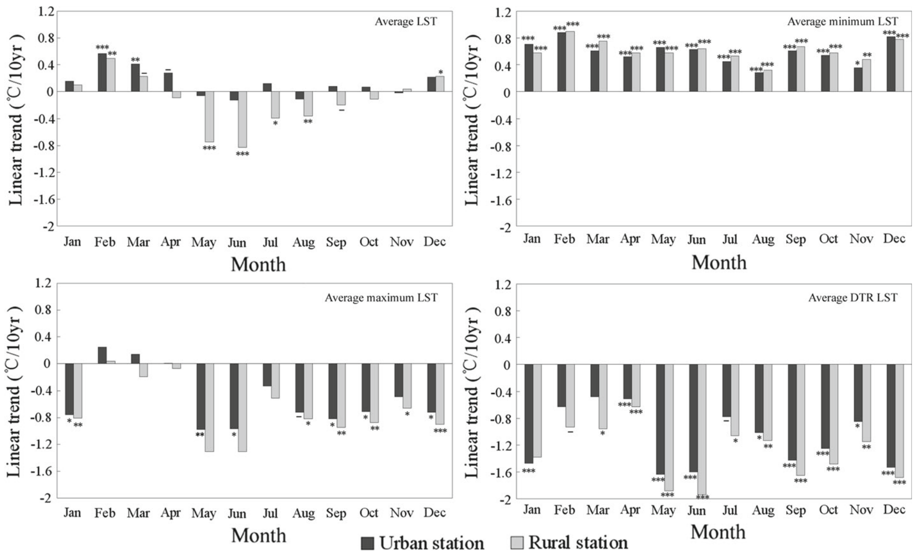

Fig. 3 Linear trends of monthly mean, minimum and maximum LST and ΔLST at the Shijiazhuang urban and rural stations during 1965–2012. *Significant at the 0.05 level, **significant at the 0.01 level, and *** significant at the 0.001 level

The trends in annual and seasonal mean minimum LST are significantly positive at the Shijiazhuang station and the two rural stations. The trends in annual mean minimum LST for the urban and rural stations are 0.59 and 0.62 °C (10 year)$^{-1}$, respectively, which are significant at the 0.001 level. The strongest increase in minimum LST occurs in winter, followed by spring, with the weakest trends in autumn and summer. The monthly mean minimum LST trend for each month is significantly positive. The trends are weak in November at the urban and rural stations, but are still significant at the 0.05 level. The positive trends in the other months are all significant at the 0.001 level, with the strongest increase found in February.

The annual mean maximum LST at stations in and around Shijiazhuang show obvious negative trends compared with the significant increases in annual mean minimum LST, amounting to −0.51 and −0.70 °C (10 year)$^{-1}$ for the urban and rural stations, respectively, and are significant at the 0.001 level. The seasonal mean maximum LST at the urban and the rural stations also display negative trends, with the negative trend at the urban station significant in summer and autumn, but not in spring and winter. All the seasonal negative trend in maximum LST at the rural stations are strongly significant, particularly in summer and autumn. The monthly mean maximum LST at the urban station has a slightly positive trend from February to April, but negative for all other months, with the strongest trend in May. Apart from a weak positive trend in February, the monthly mean trend in maximum LST at the rural stations is also negative, and significant in January and August–December.

Strongly significant negative trends are observed in the annual and seasonal mean ΔLST at both the urban and the rural stations during 1965–2012, reaching −1.1 and −1.32 °C (10 year)$^{-1}$, respectively, which are significant at the 0.001 level. The negative trend in autumn is the greatest, followed by those in winter and summer, whereas the trend in spring is weak. Negative trends in the monthly mean diurnal LST range (ΔLST) at the urban

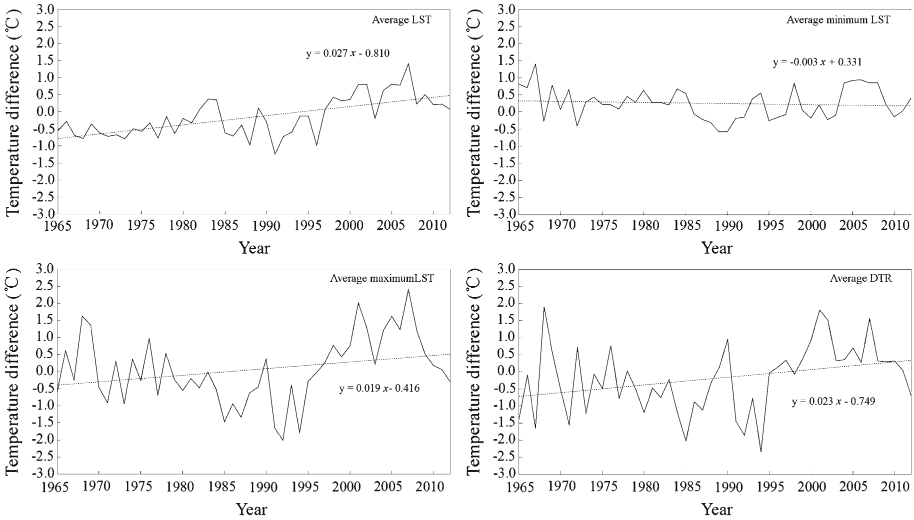

Fig. 4 Difference of annual mean LST, mean minimum (maximum) LST, and mean ΔLST between Shijiazhuang station and the rural stations during 1965–2012

Table 3 Urbanization effects (°C (10 year)$^{-1}$) and urbanization contributions (%) for annual and seasonal mean LST, mean minimum (maximum) LST, and mean ΔLST at the Shijiazhuang station during 1965–2012

	Mean LST		Mean minimum LST		Mean maximum LST		Mean ΔLST	
	UE	UC	UE	UC	UE	UC	UE	UC
Spring	0.41***	100	−0.04	–	<u>0.25</u>	92.6	0.29*	33.3
Summer	0.49***	100	−0.03	–	0.23	/	0.25	–
Autumn	0.13*	100	−0.08	–	0.15	/	<u>0.26</u>	22.2
Winter	0.04	/	0.03	–	0.16	–	0.16	–
Year	0.27***	100	−0.03	–	<u>0.19</u>	37.3	0.23*	20.9

Note that (_) denotes the significance at the 0.10 level; * significance at the 0.05 level; ** significance at the 0.01 level; *** significance at the 0.001 level. *UE* urbanization effect; *UC* urbanization contribution

and the rural stations are measurable, but are insignificant at the urban station in February and March. The strongest negative trends occur in May and June.

3.2 Effect of Urbanization

Figure 4 shows the annual mean LST difference between the Shijiazhuang station and rural stations during 1965–2012, with the difference mainly negative before 1996, but mostly positive thereafter, with a strong positive trend. The linear trend of the difference series is 0.27 °C (10 year)$^{-1}$, which is strongly significant at the 0.001 level, implying a significant urbanization effect at the Shijiazhuang station. That the urbanization contribution reaches 100% (Table 3) indicates the increase of the annual mean LST at the Shijiazhuang station is completely caused by urbanization.

The urbanization-induced land-surface warming at the Shijiazhuang station in spring and summer is 0.41 and 0.49 °C (10 year)$^{-1}$, respectively, both significant at the 0.001 level (Table 3). The relative urbanization effects on the spring and summer mean LST are large,

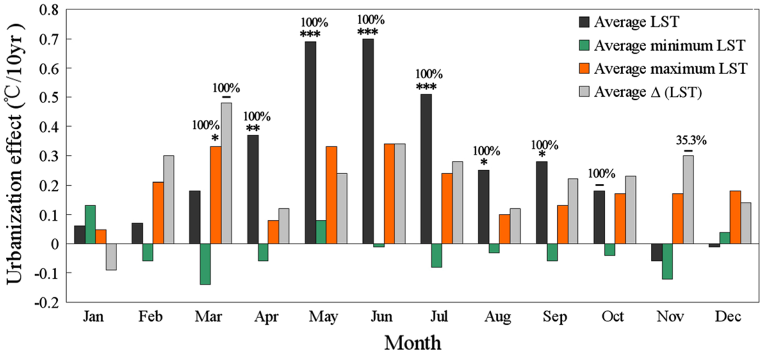

Fig. 5 Urbanization effects [°C (10 year)$^{-1}$] on the monthly mean land-surface temperature (LST), mean minimum (maximum) LST, and mean ΔLST (or average Δ(LST) as denoted in the legend) at the Shijiazhuang station during 1965–2012. The urbanization contribution (%) is given for significance urbanization effects: *significance at the 0.05 level; **significance at the level; ***significance at the 0.001 level

with the urbanization contributions reaching 100%. The urbanization effect in autumn is 0.13 °C (10 year)$^{-1}$, which is significant at the 0.05 level, and the urbanization contribution is also as high as 100%. Unlike the significant influences from urbanization in spring, summer and autumn, the seasonal mean urbanization effect in winter is small and statistically insignificant.

Figure 5 shows significant urbanization effects on the monthly mean LST trends at Shijiazhuang station from April to October, although the level of significance varies depending on the month. Strongly significant urbanization effects occur in May, June and July at the 0.001 level, with the strongest urbanization effect [0.70 °C (10 year)$^{-1}$] occurring in July; the urbanization effect in October is only marginally significant (at the 0.1 level). Urbanization contributions from April to October all reach 100%, with a negative urbanization effect found in November and December.

The urban–rural difference of annual mean minimum LST has a negative trend before about 1992, but is relatively stable thereafter (Fig. 4). The urbanization effect on the annual mean minimum LST trend at the Shijiazhuang station is negative, but small in magnitude (−0.03 °C (10 year)$^{-1}$). The urbanization effect on the seasonal and monthly mean minimum LST trends is also small.

The urban–rural difference in the annual mean maximum LST also trends negatively before 1992, but with a strong positive trend thereafter, despite trending negatively after 2006 (Fig. 4). The trend of the difference is 0.19 °C (10 year)$^{-1}$, which is marginally significant at the 0.1 level, with the urbanization contribution reaching 37% (Table 3). While the maximum LST trends due to urbanization in spring, summer, autumn and winter are 0.25, 0.23, 0.15 and 0.16 °C (10 year)$^{-1}$, respectively (Table 3), only the spring trend is marginally significant at the 0.1 level. Figure 5 further shows that the largest urbanization effect occurs in March, with a trend of 0.33 °C (10 year)$^{-1}$, which is significant at the 0.05 level, and with an urbanization contribution of 100%.

Figure 4 also shows the annual mean Δ*LST* difference between the Shijiazhuang and rural stations during 1965–2012, together with the linear trend, where a significant positive trend of 0.23 °C (10 year)$^{-1}$ at the 0.05 level is detected. As the urbanization contribution reaches 21%, approximately 20% of the trend in the annual mean Δ*LST* at the Shijiazhuang station is due to urbanization. Urbanization effects on the seasonal mean Δ*LST* in spring, summer, autumn and winter at Shijiazhuang station are 0.29, 0.25, 0.26 and 0.16 °C (10 year)$^{-1}$, respectively (Table 3). The trends are significant in spring and autumn (at the 0.05 and 0.1 levels, respectively), with the urbanization contributions for the two seasons being 33 and 22%, respectively.

The effects of urbanization on the monthly mean ΔLST at Shijiazhuang station are shown in Fig. 5, with a marginally significant positive urbanization effect detected in March and November (0.48 and 0.30 °C (10 year)$^{-1}$, respectively), and urbanization contributions reaching 100 and 35%, respectively. The effects of urbanization are small and insignificant for all other months.

4 Discussion

Studies of the effect of urbanization on the long-term temperature change have focused on trends in surface-air temperature, with little attention given to land-surface temperature (LST). The UHI effect on LST in Beijing has been investigated by comparing remote sensing data from 2001 and 2006 by Cao et al. (2010), who conclude that the daytime and nighttime-averaged LST in Beijing is higher in 2006 than in 2001. Based on a comparative analysis of LST data from one urban station and two rural stations in Nanjing from June 2009 to June 2010, Shi et al. (2012) reported a monthly mean urban–rural LST difference of 2 °C, which implies an obvious UHI effect. However, satellite data are limited because they represent a different physical quantity, and also the time series delivered by satellites are too short.

Previous work finds a significant positive trend in annual and seasonal mean LST over the previous 30–50 years in mainland China (e.g. Lu et al. 2006; Zhuo et al. 2009; Wang et al. 2009; Zhang et al. 2012), with some workers finding a significant contribution from urbanization to the observed annual and seasonal mean surface-air temperature trend in the previous 50 to 60 years (e.g. Ren et al. 2008, 2012, Zhang et al. 2010; Yang et al. 2011; Wang and Ge 2012; Ren and Zhou 2014). However, it is unclear to what extent the local urbanization process affects the positive trends in LST. For example, clear temporal and spatial differences in the urban and rural LST should be evident. Investigation of the different characteristics and temporal changes of the annual and seasonal mean LST between urban and rural stations helps understand the urban-surface climate and the observational bias in the long-term historical LST records of the urban stations.

We show that the effect of urbanization on the annual mean LST trend at Shijiazhuang station for 1962–2009 is 0.27 °C (10 year)$^{-1}$, which is significant at the 0.001 level, and the urbanization contribution reaches 100%. Therefore, the increase in the annual mean LST at Shijiazhuang station is probably entirely due to urbanization. During 1962–2009, the effect of urbanization on the annual mean surface-air temperature at Shijiazhuang station is 0.19 °C (10 year)$^{-1}$ (Bian et al. 2012; Fig. 6), which is significant at the 0.01 level, with an urbanization contribution of 68%. The effect of urbanization on both the annual mean LST and surface-air temperature at the urban station is, therefore, evident, and the effect on the annual mean LST is stronger than on the surface-air temperature (Bian et al. 2012). However, the effect of urbanization on the annual mean minimum LST trend at Shijiazhuang station is insignificant, which contrasts remarkably with the urbanization effect on the trend in surface-air temperature (Bian et al. 2012), and is as large as 0.30 °C (10 year)$^{-1}$ (significant at the 0.01 level), with an urbanization contribution reaching 53%. The urbanization effect on time series of LST mainly affects the maximum temperature, in contrast to the larger effect of urbanization on time series of the minimum surface-air temperature at the same urban station (Bian et al. 2012).

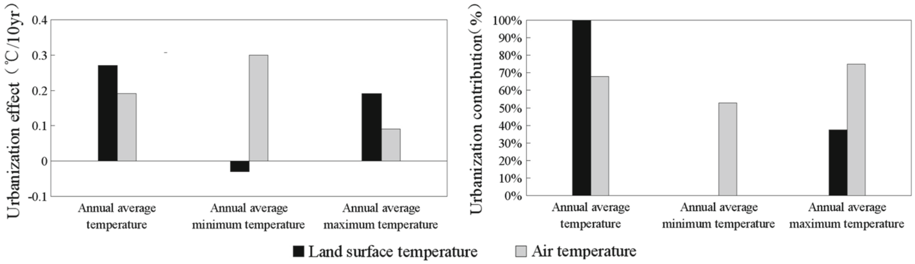

Fig. 6 Comparison of urbanization effects and contributions between the LST during 1965–2012 and the surface-air temperature during 1962–2009 at the Shijiazhuang station

Previous studies have demonstrated that urbanization significantly affects the minimum air temperature in northern China, as well as in mainland China (Chu and Ren 2005; Ren et al. 2008, 2014; Guo et al. 2009; Zhang et al. 2010; Yang et al. 2011, 2012; Wang and Ge 2012; He et al. 2013). We reveal the urbanization effect on the annual mean maximum LST to be more significant than on the annual mean minimum LST. Moreover, effects on the annual mean maximum LST differ considerably to the annual mean maximum surface-air temperature, with the former being a highly significant positive trend and the latter a weak and insignificant positive trend (Bian et al. 2012), which may be related to the properties of the city's surface, including cement, asphalt, and various industrial stone pavements. Areas of bare soil, trees, grassland, and small-scale water bodies may also be present in urban green spaces, with a wide variety of plant species having complex thermal properties. The surface temperatures of cement and asphalt pavements, which have high radiation absorption capacities, but a low heat capacity and thermal conductivity, are generally higher than those of rural and other urban surface materials exposed to direct sunlight. Thus, the maximum LST rises to much higher values for the built-up urban surfaces during daytime compared with that for other surface types or in rural areas (Chudnovsky et al. 2004). During nighttime, however, built-up areas lose heat more rapidly to the near-surface air compared with the rural areas, lowering the LST but raising the surface-air temperature, and producing a higher minimum air temperature in urban areas than in rural areas. Urban expansion enhances the different urban effects on diurnal LST and surface-air temperature, which may be the main reason why urbanization effects on the LST trends at the Shijiazhuang station exhibit a completely opposite diurnal characteristic compared with air temperature trends.

The annual urban–rural LST difference and its increase with time may also be related to the increase in annual mean UHI effect, which may be important in increasing the urban LST by increasing heat transfer from the lower atmosphere to the ground during the evening when the air temperature in the urban boundary layer is higher than the LST, in addition to the direct influence arising from the differences in surface features between urban and rural areas. Therefore, the contrasts of both the surface materials and the higher air temperature of the lower boundary layer between the urban and rural areas may have contributed to the urban–rural LST difference and its positive trend observed in the urban station.

The heat released by human activity, referred to as artificial heat release, and which warms the lower boundary layer (Shi et al. 2010), may also contribute to the increased surface-air temperature, LST and UHI intensity. Feng et al. (2012) examined the effect of artificial heat release on the regional and local climate of China using the urban-canopy model coupled with the Weather Research and Forecasting model, finding a large influence of artificial heat release on surface-air temperature, especially in winter in the highly urbanized Yangtze

Delta region. The effect of urbanization on the maximum LST due to artificial heat release in summer, however, may be larger during daytime than at night in temperate cities, due to the more frequent use of air conditioners. Li et al. (2013) described an obvious positive trend for high values of LST in Beijing in the previous decade, and Zhang et al. (2015) showed a large effect of urbanization on the maximum air temperature in urban areas of Beijing during an extreme heatwave in the summer of 2010, which is related to both the effects of the underlying surface and artificial heat release. A possible mechanism for the influence of the artificial heat release on the LST is the extra heat released into the near-surface atmosphere being transferred to the surface during winter evenings and summer daytime in temperate cities such as Shijiazhuang. However, this mechanism is less effective during summer nights and winter daytime because of the higher LST temperature compared to the surface-air temperature.

It is also plausible that the observed urbanization effect on LST trends at Shijiazhuang station is partly a consequence of the absorption and scattering of solar radiation by atmospheric aerosols, with the effect of scattering being greater than that of absorption, leading to a cooling effect at the surface (Li et al. 2015). The relative increase in daytime maximum LST and decrease or small change in nighttime minimum LST at the Shijiazhuang station may also partially be the result of the decrease in atmospheric aerosol concentration in the city relative to that in the suburbs during the last two decades, stemming from the control measures taken by local governments. However, further investigation is required to support this hypothesis.

The large and significant urbanization effects on LST trends, in particular on the summer maximum LST trends at the Shijiazhuang station, affects the urban ecosystem, the environment, and human health. The increasing daytime LST during summer exacerbates the negative influence of heatwaves on climatic comfort and human health, disrupts urban ecosystems and public infrastructure, while raising new problems with the urban environment. It is also worth noting that the large urbanization effects on LST trends represent a significant bias in the LST data obtained from the current climate-observational networks used to monitor and detect the long-term change in surface temperature at regional and global scales. In this case, the bias has to be considered in future studies.

5 Conclusions

Based on LST data from the Shijiazhuang city station and two nearby rural stations in northern China during 1965–2012, we conclude the following:

(1) The annual mean LST shows a significant positive trend of 0.13 °C (10 year)$^{-1}$ at the urban station, and a significant negative trend of -0.14 °C (10 year)$^{-1}$ at rural stations, with significant positive trends of annual mean minimum LST, and significant negative trends of the annual mean maximum LST at the urban and rural stations. The annual and seasonal mean ΔLST significantly decreases at the urban and rural stations, with a larger decrease for the latter.

(2) The linear trend in the annual mean urban–rural LST difference is 0.27 °C (10 year)$^{-1}$, which is strongly significant, with an urbanization contribution of 100% indicating that the increase in annual mean LST at the Shijiazhuang station is probably due entirely to urbanization. The urbanization effects on spring, summer and autumn mean LST trends are all significant, but wintertime trends are small with an insignificant urbanization effect.

(3) While the urbanization effect is generally weak and insignificant at Shijiazhuang station for the trends in annual, seasonal and monthly mean minimum LST, it is marginally significant for the trends in annual mean and spring mean maximum LST, with the urbanization contribution for the annual mean maximum LST reaching 37%.

(4) The positive trend of the urban–rural difference of annual mean ΔLST is 0.23 °C (10 year)$^{-1}$, which is statistically significant and accounts for 21% of the overall increase of ΔLST at the urban station; urbanization effects in spring and autumn are also significant.

(5) The significant urbanization effects in the LST time series, in particular on the positive trends in summer maximum LST at Shijiazhuang station, indicate a large relative surface warming in urban areas compared with rural areas, which, in combination with the warming of the background climate, affects the urban ecosystem, the environment, and human health. However, the problem of data representativeness of the urban station for monitoring and studying large-scale climate change needs to be addressed further.

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