Theor Appl Climatol
DOI 10.1007/s00704-015-1446-6

ORIGINAL PAPER

Urbanization effects on climatic changes in 24 particular timings of the seasonal cycle in the middle and lower reaches of the Yellow River

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Received: 1 November 2014 / Accepted: 30 March 2015

Abstract Changes in the timing of the seasonal cycle are important to natural ecosystems and human society, particularly agronomic activity. Urbanization effects (UEs) on surface air temperature changes at the local scale can be strong. Quantifying the observed changes in the timing of the seasonal cycle associated with UEs or large-scale background climatic warming is beneficial for the detection and attribution of regional climate change and for effective human adaptation, particularly in China, where rapid urbanization and industrialization are occurring. In this study, long-term changes in 24 particular timings of seasonal cycle, known as the Twenty-four Solar Terms (24STs), in the middle and lower reaches of the Yellow River in China are analyzed on the basis of homogenized daily temperature data over 1961–2010. UEs on these changes are further assessed by using a rural-station network selected from 2419 meteorological stations. In terms of area mean, half of the 24STs have significantly warmed, and UEs have contributed to 0.07–0.14 °C/decade or 25.7–64.0 % of the overall warming. The climatic solar terms from mid-February to early May (September and early October) have significantly advanced (delayed) by 5–17 days (approximately 5 days) over the last 50 years; 2–4 (2–3) of these days are attributed to UEs. The contribution of urbanization to the advancing or delaying trends is 21.7–69.5 %. The implications of these quantitative results differ for farmers, urban residents, and migrant workers in cities.

1 Introduction

Changes in the timing of the seasonal cycle are important to natural ecosystems and human society, particularly agronomic activity. In the recent decade, worldwide interests have been paid to the changes in the timing of the seasons (e.g., Sparks and Menzel 2002; Thomson 2009; Kirbyshire and Bigg 2010; Dong et al. 2010; Yan et al. 2011), especially the spring season (e.g., Qian et al. 2009, 2011a; Schwartz et al. 2013) which is closely related to phenology (e.g., Crick and Sparks 1999; Schwartz et al. 2006) and the growing season length (e.g., Menzel and Fabian 1999; Song et al. 2010).

The Twenty-four Solar Terms (24STs), which are ancient Chinese terms that have been used for more than 2000 years, describe 24 particular timings in the seasonal cycle including the timings of four seasons. The 24STs reflect not only changes in the climate but also changes in phenology and crop growth (Fig. 1 and Table 1). For example, the solar term of Waking of Insects indicates the time that insects wake from hibernation. The 24STs originated from the ancient Yellow River Basin in China and spread to other East Asian countries, such as Korea, Japan, and Vietnam. The 24STs were improved during the Qin and early Han Dynasties of Ancient China and were used for a calendar in the early Han Dynasty 2000 years ago (see Qian et al. 2012 for details). The 24STs were one of the greatest creations of Ancient Chinese farmers and were closely related to their agricultural activities. Historically, the 24STs have greatly contributed to agricultural development in China. Peasant proverbs that summarize climate conditions in the 24STs were preserved and were used as guidance for more

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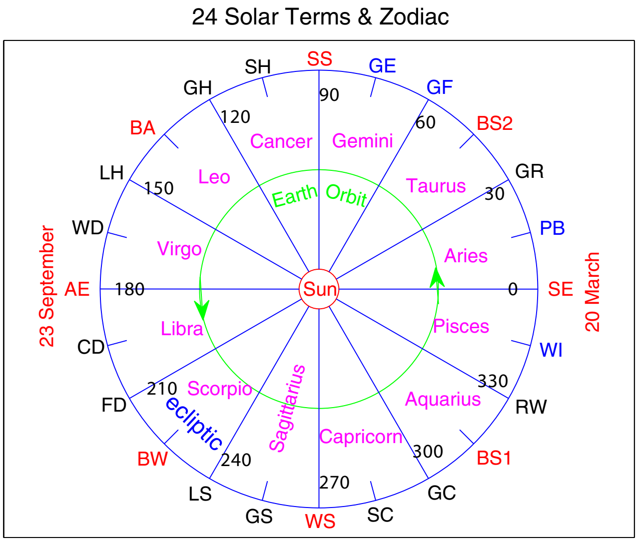

Fig. 1 Relationship between the 24STs (every 15° ecliptic longitude in the outer circle in *abbreviations*) and zodiac (every 30° ecliptic longitude in the middle circle in *magenta*). The ecliptic longitude of the first point of Aries (0° Aries) in the zodiac is consistent with SE in the 24STs. Among the 24STs, there are three major categories: eight solar terms reflect the seasonal sequence and transitions (*red*), four solar terms reflect phenology changes (*blue*), and the remaining twelve solar terms reflect the climate conditions (*black*). The abbreviations and corresponding dates of the 24STs are listed in Table 1

than 2000 years. Currently, the 24STs still have considerable referential importance to both modern agricultural activities and the daily lives of the Chinese people.

Usually, the 24STs are considered an astronomical concept, similar to the concept of the zodiac used in Western countries. Both sets of terminology reflect the periodic changes as the Earth orbits the Sun. The 24STs divide the ecliptic orbit into 24 equal 15° divisions, whereas the zodiac is a circle of twelve 30° divisions (Fig. 1). Thus, the date for each solar term in the Gregorian calendar is nearly fixed, with a variation of only 1–2 days (Table 1). However, a particular solar term is important to human activities in terms of climate conditions. By taking into account climate conditions, Qian et al. (2012) have shown on the basis of modern instrumental temperature records for the period 1961–2007 that statistically significant changes have been observed in the onset of many climatic solar terms, which are defined according to both modern climatology and the ancient calendar. Specifically, a significantly earlier onset of the climatic solar terms has occurred from early spring to early summer (6–15 days), and a significantly delayed onset of the climatic solar terms has occurred from late summer to early winter (5–6 days) in terms of the mean value in China. These climatologically defined indices reflect in detail how the seasonal cycle of temperature is changing under global warming, which will further affect changes in phenology and crop growth. Therefore, these indices are useful for monitoring climate change and its impacts. In particular, the implication of these changes for the Chinese people is that many proverbs and experiences associated with the 24STs are somehow outdated under the current climate warming.

The study of Qian et al. (2012) was on the basis of most frequently applied historical temperature dataset of the national Reference Climatic and Basic Meteorological Stations (RCBMSs, or National Stations hereafter). There are altogether 825 RCBMSs in China, many of which are located in the urban areas of towns and cities or on the edges of cities; thus, these stations inevitably contain some urbanization effects (Ren et al. 2008; Zhang et al. 2010). Many stations relocated their observation sites, e.g., from urban areas to the suburbs during the rapid urbanization in recent decades. As a result, inhomogeneity problems, which mean unnatural break points in the time series, are introduced. Therefore, several recent studies (Li et al. 2009; Li and Yan 2009; Xu et al. 2013) paid much attention to homogenize the temperature datasets. However, when the temperature data are homogenized, the urban heat island effect on the local warming trends is recovered to some extent (Hansen et al. 2001; Ren et al. 2008, 2010). This effect introduces additional local warming, superimposed on the global warming influence. The urbanization effect was not considered in the study of Qian et al. (2012); thus, its contribution remains unclear. From both scientific and human adaptation aspects, we must further quantify the urbanization bias in the changes in the 24STs to produce more robust scientific information, especially for farmers and agricultural departments.

Along with the rapid urbanization in recent decades in China, forest and crop lands substantially decreased, and the land use/land cover has dramatically changed. This urbanization has affected local and even regional temperature changes to some extent and has thus been paid more and more attentions in the scientific community (e.g., Zhou et al. 2004; Li et al. 2004; Ren et al. 2007, 2008; Hua et al. 2008; Jones et al. 2008; Zhang et al. 2010; Yang et al. 2011; Zhou and Ren 2011; Wang and Ge 2012; Wu and Yang 2013; Wang et al. 2013; Ren and Zhou 2014), particularly in terms of estimating the extent of urbanization effects. For example, Ren et al. (2008) estimated that urbanization contributed to 0.11 °C/decade of warming, which accounts for 37.9 % of the overall annual warming trend as estimated for North China over 1961–2004 using the dataset of the RCBMS. Zhang et al. (2010) reported that, regarding the increasing trend in the annual mean surface air temperature based on RCBMSs for 1961–2004, the urbanization-induced annual mean warming generally ranged from 0.06 °C/decade to 0.09 °C/decade, accounting for at least 27 % of the overall warming over the country on a whole. Ren and Zhou (2014) further estimated the urbanization effects on trends in commonly used extreme temperature indices in mainland China over 1961–2008, and found large and

Table 1 Trends in the 24STs of the area-averaged temperature in the middle and lower reaches of the Yellow River from 1961 to 2010

Solar terms	Date	Threshold (°C)	Advancing trend[a] (d/50a)	Warming trend (°C/50a)
The Beginning of Spring (BS1)	3–5 February	−3.05 (−2.53)[b]	–	2.64** (2.53**)
Rain Water (RW)	18–20 February	−0.78 (−0.29)	16.5** (16.1)**	2.80** (2.70)**
The Waking of Insects (WI)	5–7 March	2.31 (2.76)	12.8** (12.5)**	2.67** (2.58)**
The Spring Equinox (SE)	20–21 March	5.75 (6.15)	10.4** (10.2)**	1.56** (1.51)**
Pure Brightness (PB)	4–6 April	9.57 (9.93)	8.5** (8.4)**	1.91** (1.85)**
Grain Rain (GR)	19–21 April	13.09 (13.43)	7.0** (6.8)**	1.45** (1.41)**
The Beginning of Summer (BS2)	5–7 May	16.45 (16.78)	5.6** (5.2)**	1.01** (0.95)**
Grain Full (GF)	20–22 May	19.13 (19.46)	4.6* (4.1)*	0.73* (0.63)
Grain in Ear (GE)	5–7 June	21.32 (21.66)	4.7 (3.7)	0.65 (0.50)
The Summer Solstice (SS)	21–22 June	23.06 (23.42)	5.6 (3.9)	0.44 (0.33)
Slight Heat (SH)	6–8 July	24.34 (24.69)	–	0.55 (0.39)
Great Heat (GH)	22–24 July	24.81 (25.15)	–	0.29 (0.17)
The Beginning of Autumn (BA)	7–9 August	24.21 (24.54)	–	0.16 (0.04)
The Limit of Heat (LH)	22–24 August	22.59 (22.92)	−3.0 (−2.0)	0.37 (0.25)
White Dew (WD)	7–9 September	20.02 (20.36)	−4.8** (−4.5)**	0.82** (0.71)*
The Autumnal Equinox (AE)	22–24 September	17.15 (17.51)	−5.6** (−5.6)**	1.14** (1.06)**
Cold Dew (CD)	8–9 October	13.87 (14.25)	−5.3** (−5.4)**	0.79** (0.76)**
Frost's Decent (FD)	23–24 October	10.38 (10.80)	−3.9* (−3.8)*	0.67** (0.63)*
The Beginning of Winter (BW)	7–8 November	6.61 (7.07)	−3.1 (−2.4)	0.56 (0.50)
Light Snow (LS)	22–23 November	2.84 (3.34)	−3.3 (−3.0)	0.55 (0.49)
Great Snow (GS)	6–8 December	−0.38 (0.16)	−5.0* (−4.4)	1.00* (0.88)
The Winter Solstice (WS)	21–23 December	−2.83 (−2.28)	–	1.26* (1.15)*
Slight Cold (SC)	5–7 January	−4.19 (−3.64)	–	1.85** (1.72)**
Great Cold (GC)	20–21 January	−4.21 (−3.67)	–	1.51** (1.43)**

*(**) denotes that the linear trend is statistically significant at $p<0.05$ (0.01)

[a] Positive (negative) signs denote advancing (delaying) trends. En dash denotes items that are not analyzed

[b] The figures outside the parentheses are for 118 RCMBS mean whereas those inside are for the mean of all 442 stations

significant contributions from urbanization in the country on a whole.

To what extent are the observed climatic changes in the RCBMS-based 24STs related to urbanization? The present study aims to answer this question for the first time and with a focus on providing quantitative results in the middle and lower reaches of the Yellow River, where the 24STs originated. The quantification is on the basis of a recently homogenized temperature dataset of 2419 stations, including both RCBMSs and Ordinary Meteorological Stations, provided by the National Meteorological Information Center (NMIC), China Meteorological Administration (CMA). The results can be served as a scientific basis for guiding human activities and adaptation to regional climate change and for a better understanding of the actual changes in the regional surface air temperature and agronomic heat resources.

2 Research area, data, and methods

2.1 Research area

The 24STs originated in the Yellow River Basin during the Qin and early Han Dynasties. According to the territory of the Central Plains Regime, which was mainly agricultural civilization, and the path and mouth of the Yellow River at that time, the Yellow River Basin approximately contained the current southern Yellow River areas of Gansu Province, the Ningxia Hui Autonomous Region, and the Inner Mongolia Autonomous Region, and the entirety of Shaanxi Province, Shanxi Province, Henan Province, Shandong Province, Hebei Province, Beijing, and Tianjin. The key region includes seven provinces (Fig. 2a): Shaanxi Province, Shanxi Province, Henan Province, Shandong Province, Hebei Province, Beijing, and Tianjin, which are referred to as the middle and lower reaches of the Yellow River in this study. Because the exact area of origin has been lost over time, we focus on the area of the middle and lower reaches of the Yellow River.

2.2 Data

The temperature data used in this study are recently homogenized daily mean surface air temperature datasets of 2419 China stations provided by the NMIC, CMA. The data for the period of 1960–2011 are chosen because most of the stations actually started routine observations after the mid-to-late 1950s. There are altogether 442 meteorological stations in the study area (Fig. 2b), including 118 RCBMSs and 19 rural stations. Note that the RCBMSs also contain seven rural stations because we are assessing the urbanization effect contained in the RCBMS as a whole, which is widely used for climate change analysis in China. If these seven rural stations were excluded from the RCBMSs, then the urbanization contribution would be slightly larger than reported in this study.

Selecting representative rural stations is important to the estimation of the urbanization effect (Ren et al. 2008). The 19 rural stations in this study are from 138 rural/reference temperature stations network carefully selected from 2419 nationwide stations by Ren et al. (2010). Their selection was based on a comprehensive procedure that considered the spatial distribution and density of stations, the length and continuity of records, the times and distance of relocations, the population in the nearby cities/towns, and the observational environment. The 19 rural stations are relatively evenly distributed throughout the study region (Fig. 2b).

2.3 Methods

The area mean daily temperature series in the study area is first calculated. The area mean is obtained by area-weighted averaging (Jones and Hulme 1996) of the values of all the grids, which are 3°×2° (longitude×latitude). The cosine values of the latitudes of the center of the grids are used as weights. Because the rural stations are sparser than the RCBMSs, grids without observational values are omitted in the area mean procedure. In this way, the area-averaged daily temperature series for the RCBMSs, all stations and rural stations are obtained for the subsequent analysis.

The scheme for addressing leap years is the same as that used by Qian et al. (2011b): the value on 29 February is removed and the value on 28 February is replaced with the average value for 28 and 29 February. Thus, the effect of the leap year is taken into account, and the number of days in each year is always 365, facilitating the subsequent metric analysis. The method used to determine the 24 climatic solar terms is the same as that of Qian et al. (2012), which took advantage of a temporally local and adaptive filter named the ensemble empirical mode decomposition (EEMD) (Wu and Huang 2009; Huang and Wu 2008). This method is an improved version of empirical mode decomposition (EMD) (Huang et al. 1998; Huang and Wu 2008) and is used in many climate change studies (e.g., Qian et al. 2009; Wu et al. 2011; Ji et al. 2014). Because of the synoptic fluctuation in the raw daily temperature series, the raw value on each onset date of the solar term does not truly reflect climate change. Moreover, a given threshold may have multiple intersections with the daily temperature, leading to multiple options for the timing in a year. The running mean method does not satisfactorily address this issue (Qian et al. 2009, 2011a). Based on the scheme proposed by Qian et al. (2009), which used EEMD to filter out high-frequency intra-annual noise, one can adaptively and uniquely determine the timing of each of the 24 climatic solar terms (Qian et al. 2012). The detailed procedures can be found in Qian et al. (2012). A brief introduction is as follows.

1. EEMD is applied to the RCBMS mean, the all-station mean, and the rural-station mean daily temperature series to obtain the annual cycle and longer timescale

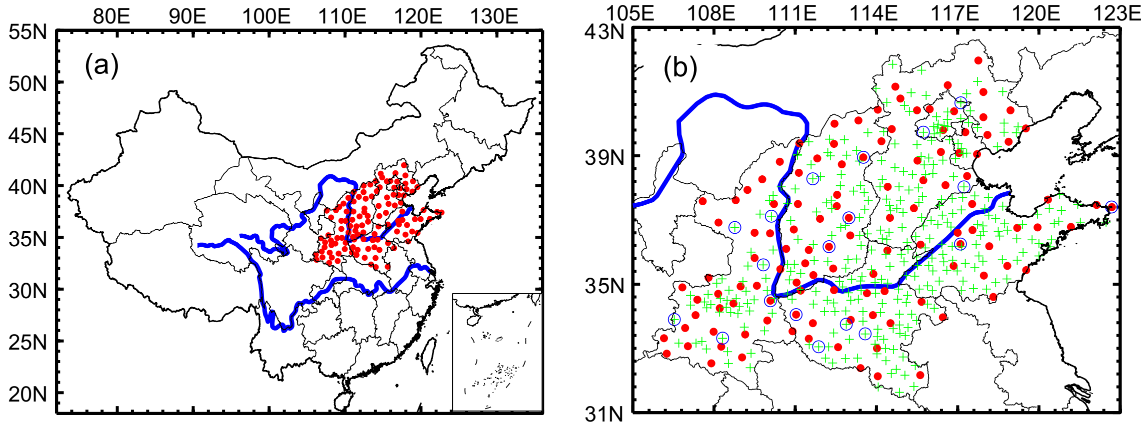

Fig. 2 Maps of the meteorological stations in the middle and lower reaches of the Yellow River. **a** 118 RCBMSs. **b** All 442 meteorological stations. The *red dots* indicate the RCMBSs, the *green crosses* indicate ordinary stations, and the *blue circles* indicate rural stations

component (ALC) (Qian et al. 2009). To remove the minor influence of the end effect, the first and last years (Qian et al. 2010) of the ALC series are excluded, leaving the period 1961–2010 for the subsequent analysis.

2. The temperature threshold (Fig. 3a; Table 1) for each solar term is determined on the basis of the climatology of the ALC for the period of 1961–1990.
3. The timing of each climatic solar term in the first (second) half of the year is determined by the date when the ALC series intersects the threshold of each solar term (except for Great Cold, Slight Cold, the Beginning of Spring, the Winter Solstice, Slight Heat, the Beginning of Autumn, and Great Heat) for the first (second) time each year. These timings are arranged chronologically for a year (Fig. 3b, c).

Linear trends in these timings are then estimated, and their significances are assessed using the Mann-Kendall test (Table 1). An advancing (delaying) trend in the timings of each climatic solar term indicates that the timings in recent years tend to occur earlier (later) than the early 1960s. Similar to Qian et al. (2012), the trends in the timing of seven solar terms (Great Cold, Slight Cold, the Beginning of Spring, the Winter Solstice, Slight Heat, the Beginning of Autumn, and Great Heat) are not investigated. In addition to the timing, the trends in the mean temperatures of each solar term (e.g., the Beginning of Spring is the average over 3–5 February) are

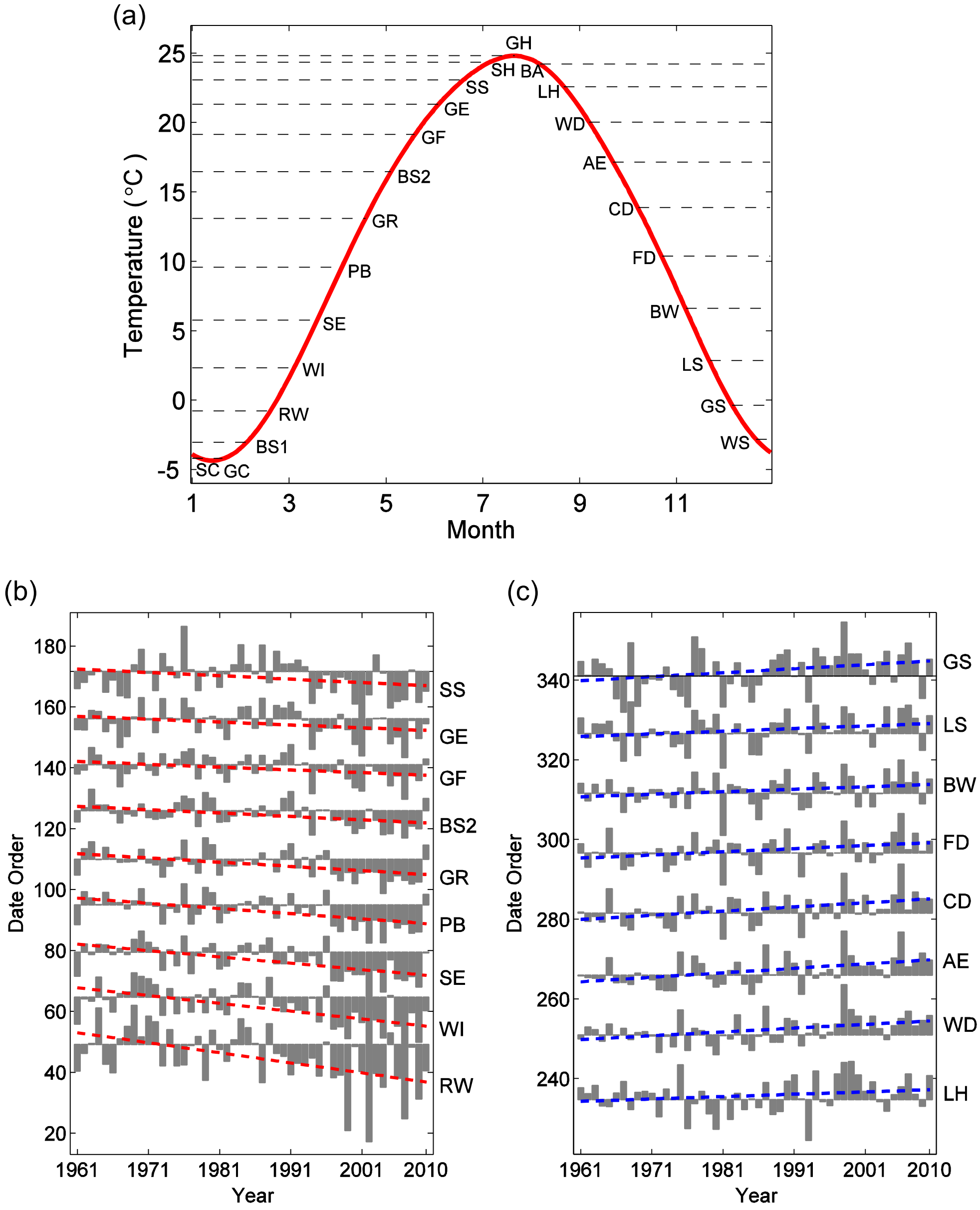

Fig. 3 The 24STs of the RCBMS mean temperature in the middle and lower reaches of the Yellow River and trends in their timings for the period 1961–2010. **a** The 24STs and their corresponding temperature thresholds. The *solid line* denotes the mean seasonal cycle based on the climatological mean ALC for the period 1961–1990, and the *dashed lines* denote the threshold for each solar term. **b** and **c** are the trends (*dashed lines*) in the timing (*bars*) of the solar terms in which **b** presents the seasonal warming period and **c** presents the seasonal cooling period. The *baselines of the bars* are 1961–1990 mean. The *abbreviations* in all panels denote the solar terms, which are listed in Table 1

also estimated according to the ALC series; the statistical significances are assessed using the Mann-Kendall test (Table 1). For convenience, in the subsequence, we refer to the "climatic solar term" simply as the "solar term" when referring to advancing or delaying trend in the solar term.

The urbanization effects on the RCBMS trend for the period 1961–2010 are assessed by a comparison with rural stations. The thresholds of the solar terms for the RCBMSs and the rural stations are determined according to their own thresholds. The urbanization effect (ΔX_{ur}) is defined as the difference between the trend in the temperature series of the RCBMS mean and that of the rural-station mean. The urbanization contribution (C_{u}) is defined as the proportion that urbanization effect accounts for the overall RCBMS mean trend (Ren et al. 2008; Zhang et al. 2010; Zhou and Ren 2011; Ren and Zhou 2014). The detailed formulas are as follows.

$$\Delta X_{\mathrm{ur}} = X_{\mathrm{u}} - X_{\mathrm{r}} \tag{1}$$

$$C_{\mathrm{u}} = \left| \Delta X_{\mathrm{ur}} \big/ X_{\mathrm{u}} \right| \times 100\% = \left| (X_{\mathrm{u}} - X_{\mathrm{r}}) \big/ X_{\mathrm{u}} \right| \times 100\% \tag{2}$$

where X_{u} indicates the linear trend in the RCBMS mean series, and X_{r} indicates the linear trend in the rural-station mean. The linear trend is estimated by the ordinary least squares method. C_{u} is only calculated when the urbanization effect is statistically significant.

3 Analysis

3.1 Characteristics of climatic changes in the 24STs

Figure 3a and Table 1 present the basic characteristics of the climatological mean 24STs of the RCBMS mean over the study area. The Great Cold (−4.21 °C) is the coldest solar term, and the Great Heat (24.81 °C) is the warmest solar term. From the Beginning of Spring to Rain Water, the temperature is below 0 °C. After the Waking of Insects, the temperature rises above 0 °C and reaches approximately 10 °C during Pure Brightness (9.57 °C). From a phenological perspective, plants have already flourished on Pure Brightness in this region. Thus, 5 °C, which is observed between the Waking of Insects and the Spring Equinox, may be more suitable than 10 °C as the temperature threshold for the timing of the spring onset. This result is consistent with the mean conditions in China (Qian et al. 2012). During the Grain in Ear and the Limit of Heat, the temperature is above 22 °C. After the Beginning of Winter, the temperature drops below 5 °C.

Under the current warming climate, climatic changes in the 24STs are evident. On the one hand, Fig. 3b shows that in terms of the RCBMS mean, the solar terms from early spring to early summer have advanced. Among these solar terms, seven are statistically significant ($p<0.05$) (Table 1): Rain Water, the Waking of Insects, the Spring Equinox, Pure Brightness, Grain Rain, the Beginning of Summer, and Grain Full; the first six solar terms are statistically highly significantly ($p<0.01$) and have advanced by 5–17 days over the last 50 years. In particular, the advance for Rain Water is the largest at 16.5 days (i.e., half a month earlier in recent years than in the early 1960s in terms of the timing of the temperature threshold occurrence of Rain Water). The characteristics that the solar terms during spring and summer have widely advanced, and that Rain Water has advanced largest, is generally consistent with the mean conditions in China (Qian et al. 2012). However, the trends in the solar terms during early summer, such as Grain Full and the Summer Solstice, in the middle and lower reaches of the Yellow River are not significant. This insignificance is mainly attributable to the insignificant trends along the sides of the lower reaches of the Yellow River, as reflected by the spatial patterns in Qian et al. (2012). On the other hand, Fig. 3c shows that in terms of the RCBMS mean, the solar terms from late summer to early winter all have delayed. Three solar terms (White Dew, the Autumnal Equinox, and Cold Dew) have trends statistically highly significant (Table 1). They have delayed by approximately 5 days over the last 50 years. The delaying trends in Frost's Decent and Great Snow are statistically significant. The advancing or delaying trends in the solar terms are closely related to the warming trends of all the solar terms (Table 1), reflecting a warming tendency of the entire seasonal cycle over the last 50 years. Two thirds of the warming trends of the 24 solar terms are statistically significant, except for those of solar terms during summer and late autumn. Half of the warming trends of the 24 solar terms (the Beginning of Spring, Rain Water, the Waking of Insects, the Spring Equinox, Pure Brightness, Grain Rain, the Beginning of Summer, White Dew, the Autumnal Equinox, Cold Dew, Slight Cold, and Great Cold) are statistically highly significant. The warming rates of solar terms during January and early April are most rapid, by more than 1.5 °C over the last 50 years. Among these warming trends, Rain Water is the largest (2.80 °C over the last 50 years). This rapid warming trend leads to the largest advancing trend in Rain Water. Compared to the results of the entire China average reported in Qian et al. (2012), the trends in the timing or mean temperature of the solar terms from January to April in the study area here are larger, whereas those during other months are smaller.

When using all 442 meteorological stations including both the RCBMSs and Ordinary Meteorological Stations in the study area for the above analyses, the area-averaged results (Table 1) are similar to those using the RCBMSs. The temperature thresholds based on the all-station mean are slightly higher than those based on the RCBMS mean because both the average latitude and the average elevation of all stations are slightly lower than those of the RCBMSs. However, the advancing or delaying trends and the warming trends in the solar terms based on the RCBMS mean are all larger than those based on the all-station mean (Table 1), implying that urbanization effects on the trends based on the RCMBS mean are evident.

3.2 Urbanization effects on climatic changes in the solar terms

In terms of the annual mean temperature (Fig. 4a), the RCBMS mean temperature has warmed at a rate of 0.25 °C/decade, whereas the rural-station mean temperature has warmed at a rate of 0.14 °C/decade. Both of these warming trends are statistically highly significant. If the warming trend based on the rural-station mean is considered the regional background warming, then the urbanization effect on the RCBMS mean warming is 0.11 °C/decade, and the urbanization contribution is 42.4 %. These two magnitudes are generally consistent with the estimations in North China by Ren et al. (2008). The time series of the difference between the RCBMS mean and rural-station mean (Fig. 4b) is further assessed using the Mann-Kendall test. The result shows that the urbanization effect is statistically highly significant and is accelerating the RCBMS temperature rise compared with the rural stations (Fig. 4b).

The urbanization effects on the warming trends in the solar terms, whose warming trends are statistically highly significant, range from 0.07 to 0.14 °C/decade (Table 2). These urbanization effects are all statistically highly significant. Among these urbanization effects, Cold Dew experiences the weakest effect, whereas Rain Water and the Waking of Insects experience the largest effects. Note that Rain Water has warmed the most but not because its urbanization effect is greatest: the warming trend is still largest even when the urbanization effect is removed. This result implies that the climate background determines the larger warming trend for Rain Water (transition period between late winter and early spring) than for the other solar terms. However, the urbanization effect and urbanization contribution differ. For example, the urbanization effect on the warming trend for Rain Water is the largest; however, the urbanization contribution is only 25.7 %, which is the lowest contribution of the twelve solar terms with highly significant warming trends. In contrast, urbanization contributions for the Beginning of Summer (transition period between spring and summer) and for White Dew (transition period between summer and autumn) exceed 50 %, which is much larger than that for Rain Water. The largest contribution is from White Dew (64.0 %). Ren et al. (2008) and Zhang et al. (2010) reported that in terms of the RCMBSs in North China, the urbanization effect is greatest in winter, whereas the urbanization contribution is largest in summer; this conclusion is generally consistent with our result.

In terms of the extreme cold and hot solar terms, the annual occurrence of extreme cold (hot) days, as counted by the number of days with raw temperatures below (above) the threshold of Great Cold (Great Heat), has significantly decreased (Fig. 5) at a rate of 3.73 days/decade (slightly increased, figure not shown). The annual occurrence of extreme cold days has decreased by 40.3 % in the last 10 years (2000s) relative to the first 10 years (1960s). Compared with the rural-station mean, the urbanization effect has accelerated the reduction in the occurrence of extreme cold days for the RCMBS mean by −0.68 days/decade. The urbanization contribution is 18.2 %.

In terms of the advancing or delaying trends in the solar terms, the urbanization effects for nine solar terms (Rain

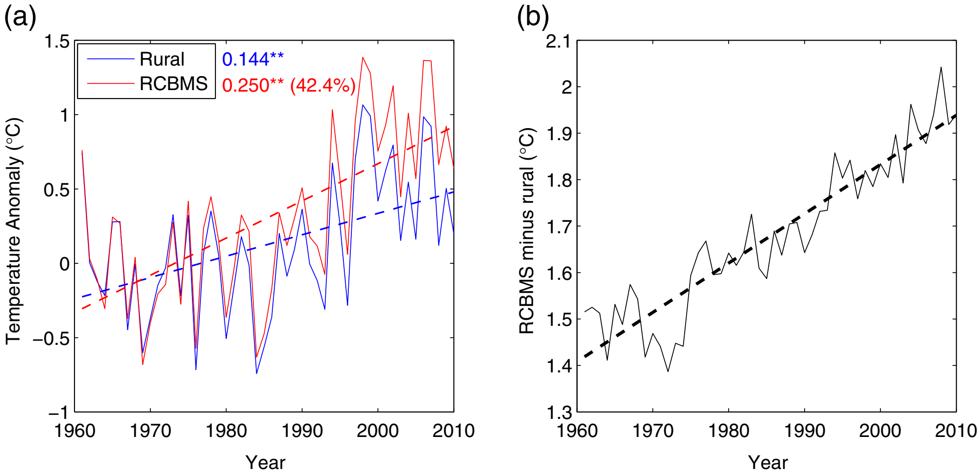

Fig. 4 Urbanization effect on changes in the RCBMS mean annual temperature (*red line*) in the middle and lower reaches of the Yellow River for the period 1961–2010. **a** Temperature anomalies (relative to 1961–1990) for the RCBMS mean (*red line*) and for the rural-station mean (*blue line*). The *blue line* has subtracted the 1961–1970 average temperature difference between the rural-station mean and the RCBMS mean such that the two time series have the same 10-year average during the 1960s. The *dashed lines* indicate the corresponding linear trends. *Double asterisks* denotes that the linear trend is statistically significant at the 1 % level. **b** The difference (*solid line*) between the RCBMS mean and rural-station mean and the corresponding linear trend (*dashed line*)

Table 2 Urbanization effects (UEs) and urbanization contributions (UCs) of climatic changes in the solar terms that have significantly changed in terms of the RCBMS mean temperature in the middle and lower reaches of the Yellow River from 1961 to 2010

Solar terms	Advancing trend[a]		Warming trend	
	UE (d/50a)	UC (%)	UE (°C/decade)	UC (%)
The Beginning of Spring (BS1)	–	–	0.14**	25.7
Rain Water (RW)	3.6**	21.7	0.14**	25.7
The Waking of Insects (WI)	2.8**	21.8	0.14**	26.9
The Spring Equinox (SE)	2.6**	25.1	0.09**	29.4
Pure Brightness (PB)	2.7**	31.3	0.13**	34.3
Grain Rain (GR)	2.8**	40.2	0.12**	42.3
The Beginning of Summer (BS2)	3.1**	55.0	0.12**	57.6
White Dew (WD)	−3.3**	69.5	0.11**	64.0
The Autumnal Equinox (AE)	−2.4**	43.8	0.11**	48.4
Cold Dew (CD)	−2.2**	41.0	0.07**	46.6
Slight Cold (SC)	–	–	0.10**	26.9
Great Cold (GC)	–	–	0.08**	26.4

[a] Same as in Table 1a

** denotes that the linear trend is statistically significant at the 1 % level

Water, the Waking of Insects, the Spring Equinox, Pure Brightness, Grain Rain, the Beginning of Summer, White Dew, the Autumnal Equinox, and Cold Dew), whose advancing or delaying trends are highly significant, are as follows. The urbanization effects advanced the solar terms during spring and summer by additional 2–4 days over the last 50 years; Rain Water was the largest by 3.6 days. The urbanization effects delayed the solar terms during autumn by additional 2–3 days (Table 2). Here "additional" is relative to the local scale advancing or delaying trends introduced by changes in the climate background. For example, for Rain Water, there is an overall 16.5 days advance over the last 50 years, with a 12.9-day advance introduced by changes in the climate background and a 3.6-day advance introduced by urbanization. The trend introduced by changes in the climate background is also statistically highly significant. Figure 6 shows the temporal evolutions of the urbanization effects on the advancing and delaying trends in the nine solar terms. Other than the interannual variability, the urbanization trend is apparent for each solar term. All of the urbanization effects are statistically significant (Table 2). The urbanization contributions to the advancing or delaying trends in the nine solar terms range 21.7–69.5 %. Rain Water has the smallest contribution, whereas White Dew has the largest contribution. This ranking is consistent with the urbanization contributions to the warming trends of the solar terms.

4 Summary and discussion

Climatic changes in the 24STs in the middle and lower reaches of the Yellow River, where the 24STs originated and where the 24STs are the most suitable tool for arranging the agronomic activities, are examined on the basis of homogenized daily temperature data for the period 1961–2010. These changes include trends in the timing of each solar term, the trends in the mean temperature of each solar term, and the trends in the occurrence of extreme cold and hot days. A focus is estimating the urbanization effects on these changes over the last 50 years using a rural-station network. The main conclusions are summarized as follows.

1. In terms of the area average based on the RCBMSs over the last 50 years, the solar terms from early spring to early summer (Rain Water, the Waking of Insects, the Spring Equinox, Pure Brightness, Grain Rain, and the Beginning of Summer) have highly significantly advanced by 5–17 days. Rain Water advanced the most at 16.5 days. The solar terms during autumn (White Dew, the Autumnal Equinox, and Cold Dew) have highly significantly delayed by approximately 5 days.
2. The advancing or delaying trends in the solar terms are closely related to a warm shift in the entire seasonal cycle. Half of the 24STs have highly significantly warmed. The solar terms from January to early April have warmed more than 1.5 °C. Rain Water warmed the most at 2.80 °C over the last 50 years. The annual occurrence of extreme cold days has decreased at a rate of 3.73 days/decade and by 40.3 % in the 2000s relative to the 1960s.
3. In terms of the RCBMS mean, the urbanization effect on the annual warming trend is 0.11 °C/decade (42.4 % of the overall warming); the urbanization effect on the solar term warming trends with a high significance level is 0.07–0.14 °C/decade. These urbanization effects are all

statistically highly significant. The urbanization effect is weakest in Cold Dew and strongest in Rain Water and the Waking of Insects. However, in terms of urbanization contributions, Rain Water is smallest (25.7 %), whereas the Beginning of Summer and White Dew both register a contribution more than 50 %. The largest value is White Dew (64.0 %). The urbanization effect has accelerated the reduction in the occurrence of extreme cold days by −0.68 days/decade (18.2 % of the overall decrease).

4. In terms of the RCBMS mean, the urbanization effects have advanced the solar terms during spring and summer (Rain Water, the Waking of Insects, the Spring Equinox, Pure Brightness, Grain Rain, and the Beginning of Summer) by additional 2–4 days over the last 50 years. Rain Water has the strongest urbanization effect (additional 3.6 days). The urbanization effects have delayed the solar terms during autumn (White Dew, the Autumnal Equinox, and Cold Dew) by additional 2–3 days. The corresponding urbanization contributions are 21.7–69.5 %, with the largest contribution in White Dew (early September), and the smallest contribution

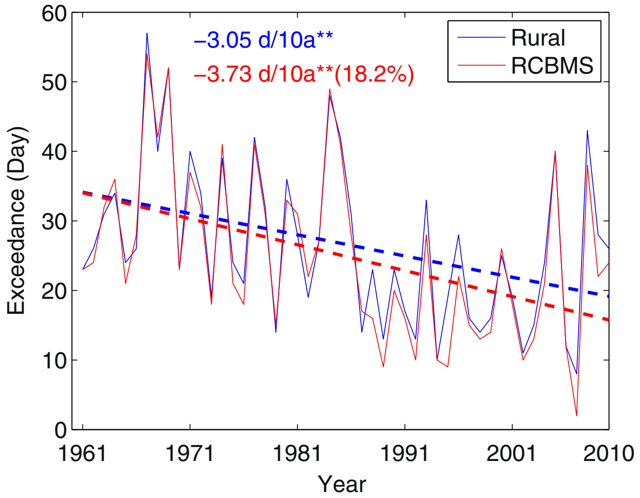

Fig. 5 Urbanization effect on changes in the RCBMS mean annual occurrence of extreme cold days (*red line*) in the middle and lower reaches of the Yellow River for the period 1961–2010. The *blue line* indicates the rural-station mean. The *dashed lines* indicate the corresponding linear trends. *Double asterisks* denotes that the linear trend is statistically significant at the 1 % level

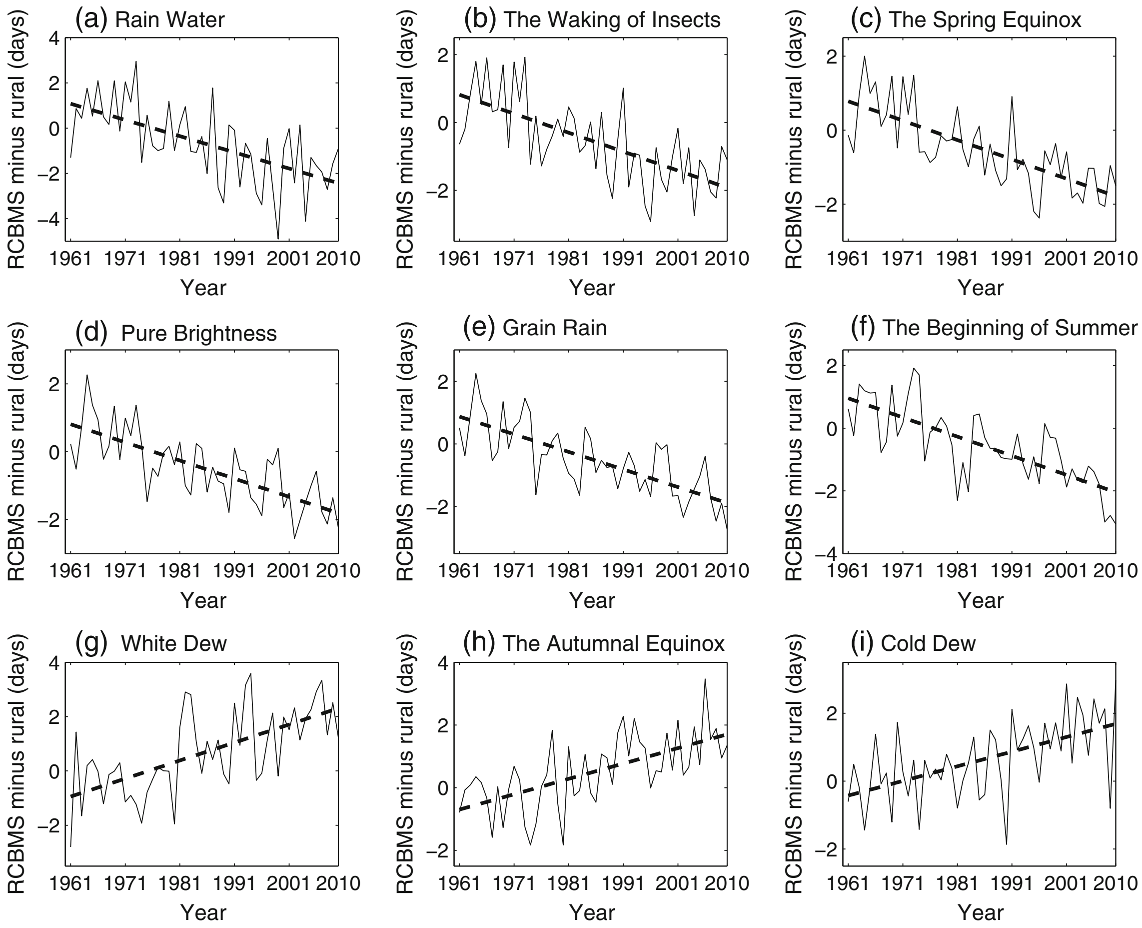

Fig. 6 Urbanization effect on changes in the RCBMS mean timing of the solar terms whose advancing or delaying trends are statistically significant at the 1 % level in the middle and lower reaches of the Yellow River for the period 1961–2010. The *solid lines* indicate the difference between the RCBMS mean and the rural-station mean, and the *dashed lines* indicate the corresponding linear trends

in Rain Water (mid-February) when the warming and advancement are greatest.

The implications of the above results for adaptation to climate change are as follows. First, under the background of global climate warming, many of the 24STs, which are frequently followed by famers in the middle and lower reaches of the Yellow River, have changed significantly from a climatological perspective. In particular, the solar terms during the spring plowing and sowing period have advanced significantly. To adapt to climate change, farmers should perform agricultural activities several days earlier. However, the quantitatively estimated results of changes in the surface air temperature and onset timing of each solar term based on frequently applied homogenized RCBMS data somewhat overestimate the background or regional long-term warming trends. This overestimation must be taken into account or adjusted in practice for farmers and local governments to adapt to the actual or background changes in climate and the timing of the 24STs. Second, for people living in cities or nearby areas, these quantitatively estimated results using the RCBMS data are suitable because they reflect local urbanization effects superimposed on the global or regional climate warming background. Thus, climatic changes in the 24STs in cities are more prominent and faster than those in the rural areas. Therefore, the traditional activities of city residents from the experience based on the 24STs should be adjusted according to the RCBMS results. Finally, under the current urbanization pathway, increasingly more farmers have been becoming city residents as the countryside is converted into towns or cities, particularly in the plains areas. These people will experience higher temperatures on a given day and an earlier arrival of the same temperature during spring and early summer, for example, the summer will arrive earlier than in the countryside. Therefore, people's experience based on the 24STs need to be adjusted to adapt to the new situation of urban warming superimposed on global climate warming.

Acknowledgments This work was supported by the National Basic Research Program of China (Grant 2011CB952003), the Jiangsu Collaborative Innovation Center for Climate Change, and the Ministry of Science and Technology of China (Grant GYHY201206012).

References

Crick HQP, Sparks TH (1999) Climate change related to egg-laying trends. Nature 399:423–424

Dong WJ, Jiang YD, Yang S (2010) Response of the starting dates and the lengths of seasons in Mainland China to global warming. Clim Chang 99:81–91

Hansen J, Ruedy R, Sato M, Imhoff M, Lawrence W, Easterling D, Peterson T, Karl T (2001) A closer look at United States and global surface temperature change. J Geophys Res 106:23947–23963. doi:10.1029/2001JD000354

Hua LJ, Ma ZG, Guo WD (2008) The impact of urbanization on air temperature across China. Theor Appl Climatol 93:179–194

Huang NE, Wu Z (2008) A review on Hilbert-Huang transform: method and its applications to geophysical studies. Rev Geophys 46, RG2006

Huang NE, Shen Z, Long SR, Wu MC, Shih HH, Zheng Q, Yen N-C, Tung CC, Liu HH (1998) The empirical mode decomposition and the Hilbert spectrum for nonlinear and nonstationary time series analysis. Proc R Soc A Math Phys Eng Sci 454:903–995

Ji F, Wu ZH, Huang JP, Chassignet EP (2014) Evolution of land surface air temperature trend. Nat Clim Chang. doi:10.1038/nclimate2223

Jones PD, Hulme M (1996) Calculating regional climatic time series for temperature and precipitation: methods and illustrations. Int J Climatol 16:361–377

Jones PD, Lister DH, Li Q (2008) Urbanization effects in large-scale temperature records, with an emphasis on China. J Geophys Res 113, D16122. doi:10.1029/2008JD009916

Kirbyshire AL, Bigg GR (2010) Is the onset of the English summer advancing? Clim Chang 100:419–431

Li Z, Yan ZW (2009) Homogenized daily mean/maximum/minimum temperature series for China from 1960–2008. Atmos Ocean Sci Lett 2:237–243

Li Q, Zhang H, Liu X, Huang J (2004) Urban heat island effect on annual mean temperature during the last 50 years in China. Theor Appl Climatol 79:165–174

Li Q, Zhang H, Chen J, Li W, Liu X, Jones PD (2009) A mainland China homogenized historical temperature dataset of 1951–2004. Bull Am Meteorol Soc 90:1062–1065

Menzel A, Fabian P (1999) Growing season extended in Europe. Nature 397:659

Qian C, Fu C, Wu Z, Yan Z (2009) On the secular change of spring onset at Stockholm. Geophys Res Lett 36, L12706. doi:10.1029/2009GL038617

Qian C, Wu Z, Fu CB, Zhou TJ (2010) On multi-timescale variability of temperature in China in modulated annual cycle reference frame. Adv Atmos Sci 27:1169–1182

Qian C, Fu CB, Wu Z, Yan ZW (2011a) The role of changes in the annual cycle in earlier onset of climatic spring in northern China. Adv Atmos Sci 28:284–296

Qian C, Yan ZW, Wu Z, Fu CB, Tu K (2011b) Trends in temperature extremes in association with weather-intraseasonal fluctuations in eastern China. Adv Atmos Sci 28:297–309

Qian C, Yan ZW, Fu CB (2012) Climatic changes in the Twenty-four Solar Terms during 1960–2008. Chin Sci Bull 57(2):276–286

Ren GY, Zhou YQ (2014) Urbanization effect on trends of extreme temperature indices of national stations over Mainland China, 1961–2008. J Clim 27:2340–2360

Ren GY, Chu ZY, Chen ZH, Ren YY (2007) Implications of temporal change in urban heat island intensity observed at Beijing and Wuhan stations. Geophys Res Lett 34, L05711. doi:10.1029/2006GL027927

Ren G, Zhou Y, Chu Z, Zhou J, Zhang A, Guo J, Liu X (2008) Urbanization effects on observed surface air temperature trends in North China. J Clim 21:1333–1348

Ren GY, Zhang A, Chu ZY, Zhou JX, Ren YY, Zhou YQ (2010) Principles and procedures for selecting reference surface air temperature stations in China (in Chinese). Meteorol Sci Technol 38(1):78–85

Schwartz MD, Ahas R, Aasa A (2006) Onset of spring starting earlier across the Northern Hemisphere. Glob Chang Biol 12:343–351

Schwartz MD, Ault TR, Betancourt JL (2013) Spring onset variations and trends in the continental United States: past and regional assessment using temperature-based indices. Int J Climatol 33:2917–2922

Song Y, Linderholm HW, Chen D, Walther A (2010) Trends of the thermal growing season in China, 1951–2007. Int J Climatol 30:33–43

Sparks TH, Menzel A (2002) Observed changes in seasons: an overview. Int J Climatol 22:1715–1725

Thomson DJ (2009) Shifts in season. Nature 457(22):391–392

Wang F, Ge QS (2012) Estimation of urbanization bias in observed surface temperature change in China from 1980 to 2009 using satellite land-use data. Chin Sci Bull 57:1708–1715. doi:10.1007/s11434-012-4999-0

Wang J, Yan ZW, Li Z, Liu WD, Wang YC (2013) Impact of urbanization on changes in temperature extremes in Beijing during 1978–2008. Chin Sci Bull 58:4679–4686. doi:10.1007/s11434-013-5976-y

Wu Z, Huang NE (2009) Ensemble empirical mode decomposition: a noise-assisted data analysis method. Adv Adapt Data Anal 1:1–41

Wu K, Yang XQ (2013) Urbanization and heterogeneous surface warming in eastern China. Chin Sci Bull 58:1363–1373. doi:10.1007/s11434-012-5627-8

Wu Z, Huang NE, Wallace JM, Smoliak BV, Chen X (2011) On the time-varying trend in global-mean surface temperature. Clim Dyn 37:759–773

Xu W, Li Q, Wang XL, Yang S, Cao L, Feng Y (2013) Homogenization of Chinese daily surface air temperatures and analysis of trends in the extreme temperature indices. J Geophys Res Atmos 118:9708–9720. doi:10.1002/jgrd.50791

Yan ZW, Xia JJ, Qian C, Zhou W (2011) Changes in seasonal cycle and extremes in China during the period 1960–2008. Adv Atmos Sci 28:269–283

Yang X, Hou Y, Chen B (2011) Observed surface warming induced by urbanization in east China. J Geophys Res 116, D14113. doi:10.1029/2010JD015452

Zhang AY, Ren GY, Zhou JX, Chu ZY, Ren YY, Tang GL (2010) Urbanization effect on surface air temperature trends over China. Acta Meteorol Sin 68:957–966

Zhou YQ, Ren GY (2011) Change in extreme temperature event frequency over mainland China, 1961–2008. Clim Res 50:125–139

Zhou L, Dickinson RE, Tian Y, Fang J, Li Q, Kaufmann RK, Tucker CJ, Myneni RB (2004) Evidence for a significant urbanization effect on climate in China. Proc Natl Acad Sci U S A 101(26):9540–9544. doi:10.1073/pnas.0400357101