Long-Term Surface Air Temperature Trends Over Mainland China

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Summary

Based on a dataset of national reference and basic stations, which have been quality controlled and inhomogeneity processed, updated surface air temperature (SAT) series of the past 67 (1951–2017) and 113 (1905–2017) years for mainland China are constructed and analyzed. The new temperature series show significant warming trends of 0.24°C/10yr and 0.09°C/10yr respectively for the two periods. The rapid regional warming generally begins from the mid-1980s, about a decade later than the northern hemisphere average SAT change. Warming during the period of 1951–2017 is larger and more significant in the northeast, north, northwest and the Qinghai-Tibetan Plateau, and the most significant SAT increase usually occurs in winter and spring except for the Qinghai-Tibetan Plateau where winter and autumn undergo the largest warming. The slowdown of the warming can be clearly detected after 1998, especially for autumn and winter. The effect of urbanization on trends of the region averaged annual and seasonal mean SAT as calculated from the national reference and basic stations has not been adjusted, despite it being generally large and significant. In north China, the increasing trend of annual mean SAT induced by urbanization for the national stations is 0.10°C/10yr for the period 1961–2015, accounting for at least 31% of the overall annual mean warming. The contribution of urbanization to the overall warming of the past half century in Mainland China has also been summarized and discussed referring to the previous studies.

Keywords: climate change, surface air temperature, regional warming, urbanization effect, Mainland China

Introduction

The surface climate of the Earth has experienced an obvious warming since the early 1900s, and the climatic warming in regions, hemispheres, and the globe during that time has been well recognized (Brohan et al., 2006; Cane et al., 1997; Sun et al., 2017).

Climate change in Mainland China bears a good similarity to the change around the globe and northern hemisphere. This conclusion was drawn by many researchers based on datasets from the relatively densely distributed observation sites in Mainland China, especially for the past half century (e.g., Cao et al., 2013, 2016; Qian & Lin, 2004; Ren et al., 2005a, 2012, 2017;

Tang & Ren, 2005; Wang et al., 2002; Zhai & Pan, 2003; Zhao et al., 2014). The observed global and regional warming has been attributed to the increase in atmospheric concentration of greenhouse gases resulting from human activities since the pre-industrial era (Houghton et al., 2001; IPCC, 2013). The increase in Surface Air Temperature (SAT) over Mainland China in the 20th century, especially since 1950s, has been also related to the enhanced greenhouse effect (Committee on National Assessment Report on Climate Change, 2007; Ding & Ren, 2008), though other regional and local anthropogenic driving forces may have also played a role in the rapidly developing region.

It is commonly held that to detect regional climate change and especially to attribute it to any specific factors are still among the most challenging tasks facing climatologists, and more research is needed (IPCC, 2013). Different datasets applied and the varied data-processing methods in regional studies can sometimes lead to significant differences in the analysis results; inhomogeneities of instrumental data series are yet to be given more attention and to be properly adjusted: This can affect the estimated average temperature trends for some sites (Cao et al., 2016; Yan & Jones, 2008). It is also worth noting that although much attention has been paid to the effect of urbanization on the observed regional surface air temperature trend for Mainland China—and substantial progress has been made to understand the nature and magnitude of the urbanization contribution in the current SAT data series (Ren et al., 2015, 2017)—a reliable adjustment of the urbanization biases is still a big challenge. It is rather difficult to have an in-depth knowledge of the accurate rate of the SAT change on different tempo-spatial scales of regional climate change in the past century and the anthropogenic role without appropriately solving these problems.

Recognizing the difficult issues still facing Chinese climatologists, a series of studies on surface and upper air temperature change in Mainland China have been conducted since 1990s. These analyses all showed a larger and significant surface warming in Mainland China as a whole over varied periods, but it also indicates a significant effect of urbanization on the regional mean SAT trends as calculated from the national station network.

The remainder of this article consists of the following parts: the second part describes the data and methods applied, the third part summarizes major results and findings of the surface air temperature analysis for the past decades to century in the country, the fourth part gives a discussion of the urbanization effect on the estimated surface air temperature trends in the region, and the final part summarizes the main conclusions.

Data and Methods

Observational History

Modern weather and climate observations were introduced to China in the 18th century by the Western missionaries, and continuously observational records have been available for a few stations only since the late 19th century. After about 1911, modern national meteorological observations were officially started (Jie, 2018).

Before 1950, and especially during the 1940s, however, the observational stations in Mainland China were sparsely distributed. After that time, the observations were rapidly restored and developed. By the end of the 1950s, most of the country had been covered by meteorological stations. Some stations stopped observation for a few of months during the Cultural Revolution, but overall the records after 1950s were in high quality. The missing data were filled in by using climatological normal values, or by applying the average value of the neighboring days if the missing records did not surpass one day, and by interpolating using the records of the neighboring stations if exceeding one day.

A major problem with the observations would be the relocations of the stations due to the rapid urbanization over the past decades. More than two thirds of the national stations underwent relocations at least once. These led to the discontinuities of the surface records, and homogenization of the data had to be conducted. If no relocation occurred, however, another problem, the urbanization effect on the surface climate variables such as temperature and wind speed, would gradually become serious. Around 2003, the manual observations were transformed to automatous systems, which also resulted in significant inhomogeneities in the historical data series for most national stations.

Description of Data

The homogenized 1951–2017 monthly mean SAT dataset used in this study is from the National Meteorological Information Center, China Meteorological Administration (CMA). It consists of a total of 2,419 surface stations, with 34.4% of observation sites coming from national reference climate stations and national basic meteorological stations (called “national stations” hereafter), and about 65.6% from national ordinary weather stations. The 825 national stations from the dataset are used in this study. Table 1 lists the number, average distances of separation, and observation times of the three types of stations.

Table 1. Type, Number, Average Distances of Separation and Measuring Times of Observational Stations Under the China Meteorological Administration (CMA)

Type of Station	Number	Average Distances of Separation (km)	Daily Observation Times
Reference Climate Station	143	–350	24
Basic Meteorological Station	682	–150	8
Ordinary Weather Station	1594	–50	3 (4)
Total	2419		

There were fewer observational sites in the national station network in the early 1950s (Figure 1). The number was only 148 in 1951. It rapidly increased to 503 in 1956 and nearly 767 in 1960. The stations basically stand between 770 and 825 after 1960. Of these stations, 815 have kept uninterrupted recording for 30 years, 811 for 35 years, 805 for 40 years, 727 for 50 years, 548 for 60 years, and only 99 for 67 years (Table 2). In the early 1950s, not only were there fewer stations, but their spatial distribution was relatively uneven. Except for a few stations in Xinjiang Uygur Autonomous Region, there were almost no observations in other areas of western China in 1951. Since then, however, the number of stations in western China has gradually increased. And by 1956, all provinces and autonomous regions in the country were well covered by the national station network.

In order to investigate the possible effect of variation in the number of stations over time, the country average annual and seasonal mean SAT anomaly series is calculated by using different numbers of stations with varied years of uninterrupted recording for the 1951–2017 period, and their differences in mean anomaly, variance, and trend are compared (Table 2). The differences are slight, especially in variance and trend, indicating that more stations with fewer years of uninterrupted recording could be used to increase the spatial coverage of observations. The stations with at least 40 years of uninterrupted recording but that also kept up continuous recording for at least 25 years for the base period (1971~2000), are chosen for use in the analysis. There were 802 stations that met the criteria. Figure 1a shows the distribution of the stations in 1975, a representative year after 1956. Except for the northwestern part of Tibet Autonomous Region, the observational sites are comparatively even in spatial distribution. Fluctuation of numbers of stations during 1956–2017 is therefore negligibly small.

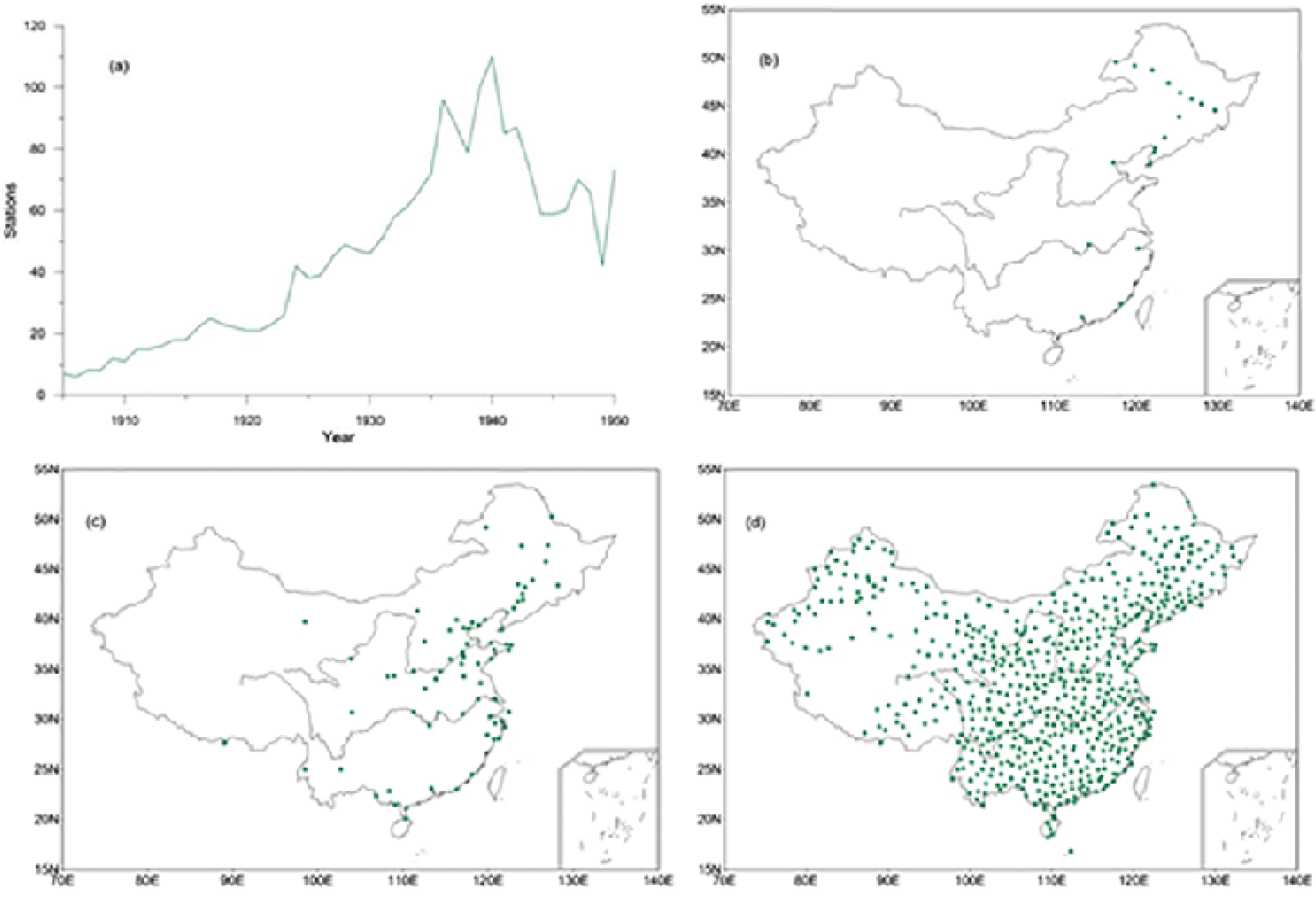

Figure 1. Distribution of surface air temperature observation sites used for this study: (a) number of stations used for constructing the 113-year temperature series before 1950; (b) 1915; (c) 1935; and (d) 1965.

In the dataset, however, there is a prominent problem caused by artificial factors, leading to inhomogeneity of the individual time series (Feng, Hu, & Qian, 2004; Li et al., 2004a; Yan, Yang, & Jones, 2001). A main cause for the inhomogeneity is relocation of stations (Feng et al., 2004; Li et al., 2004a). More than two thirds of the stations have been relocated at least once during the period investigated mainly due to the gradual deterioration in micro-environment of the observing sites, induced by the rapid urbanization in the country. Some stations in the rapidly developing regions moved more than five times. Changes in observation time, instrument types, and shelters may result in additional inhomogeneities in the SAT time series of the dataset.

Table 2. Statistics of the Country Averaged Annual Mean Surface Air Temperature Anomaly Series for the 1951–2017 Period, Constructed by Using the Data of Stations with Different Years of Uninterrupted Recording

Years of Uninterrupted Recording	30	35	40	50	60	67
No. of stations	815	811	805	727	548	99
Mean anomaly (°C)	0.09	0.09	0.09	0.09	0.07	0.08
Variance	0.31	0.31	0.31	0.31	0.32	0.32
Trend (°C/yr)	0.024	0.024	0.024	0.024	0.024	0.023

In order to minimize the influence of the artificial factors on temperature trends, the inhomogeneities of the monthly mean SAT data were adjusted (Cao et al., 2016). Referring to the method of Wang (2008), obvious breakpoints in the monthly mean SAT series of the national stations were examined using statistical analysis and station historical records or metadata, and the confirmed artificial discontinuities were corrected applying the time series of the nearby stations. The process largely erased the discontinuities identified, with most of them resulting from the station relocations; thus, the time series of individual stations became comparatively more homogeneous than the original data series. This inhomogeneity adjusted dataset of the national stations is utilized in the study.

The data for 1841–1950 are from “Temperature Data of China” previously compiled by a joint group of the former Chinese Central Meteorological Observatory and the Institute of Geophysics of the Chinese Academy of Sciences and updated by the National Meteorological Information Center, CMA. In this period, observation sites were sparsely distributed, with most of them being in eastern China. Data sites are extremely scarce in the early years in western part of the country. Changes in station locations, instruments and instrumental shelters, observation time, and statistical methods for daily and monthly averages occur for the stations, leading to obvious inhomogeneities of temperature series. Difficulties arise in checking and adjusting the inhomogeneities because of the lack of sufficient documentation in the early years.

A dataset consisting of a total of 616 stations is used to obtain the long mean SAT series. Of these stations, only 231 began recording before 1951, and the observations were mostly stopped during World War II and the Civil War (1945–1949), in particular in the period of 1941–1948. The data after 1951 are from the national station network. There are fewer stations in the early years of the pre-1950 period, and most of the available records are from the eastern provinces of the country. At the end of the 19th century, only the Beijing, Shanghai, and Hong Kong stations were in operation. For this study, 1905 is set as the starting time, by which time the monthly SAT data from 25 stations are available (Figure 1b, Figure 1c).

The deficiency of data in western China in the early years poses a problem, which may have made the national average SAT series obtained for the pre-1951 period actually more representative of eastern and central China. It is notable that the same problem was also found when researchers tried to construct the global average annual mean SAT series of the past 100–140 years (e.g., Hansen et al., 1999, 2006; Jones et al., 2012; Lawrimore et al., 2011; Polyakov et al., 2002).

The correlation coefficients, and the respective variances and temporal trends of the average annual mean SAT series for eastern and western China for the period 1951–2017 are calculated by using the methods described in section 2.2 of the paper. The dividing line for eastern and western China is 100°E meridian. Correlation coefficient between the time series is 0.90, and the variances and trends of the eastern and western series are respectively 0.31 and 0.35, and 0.23°C/10yr and 0.25°C/10yr. The correlation between the two series is statistically significant at the 99% confidence level, and no significant differences of variances and trends between them are detected. So, it is acceptable to construct a country- averaged SAT series using available data mostly from eastern China in the early stage of the period investigated.

It is extremely difficult to detect and adjust the inhomogeneities of the pre-1950 data series, which were probably caused by station relocation, instrument and instrumental shelter changes, observation time, and statistical method changes due to lack of metadata. However, the problem with changes in observation time and calculation methods for daily averages is serious, and it significantly affects the comparability between the pre- and post-1950 observations. Varied observation times and time systems were used before 1950, and when daily and monthly mean temperature are calculated, these lead to the evident inhomogeneities of the SAT time series.

In order to minimize the inhomogeneities caused by these non-climatic factors, maximum and minimum temperature records, rather than four time records a day as stipulated for the post-1950 observations by the CMA, are applied to calculate the daily and monthly mean temperature throughout the 100-year temperature series. This to a large extent avoids the inconsistences caused by the artificial factors identified above and increases the homogeneity of the temperature series. It also increases the comparability of the Chinese temperature series with the main global SAT datasets (Hansen et al., 2006; Jones et al., 2012; Lawrimore et al., 2011). For the 100-year temperature series, the inhomogeneity induced by different observation time and time systems and varied statistical methods has thus been accounted for, but the inhomogeneities probably caused by relocation of stations and upgrading of instruments have not been considered and adjusted. Tang and Ren (2005) gave a more detailed illustration of data quality control and treatment of the inhomogeneities for the long SAT dataset.

Methods

The method of Jones and Moberg (2003) is adopted for constructing the country-averaged SAT anomaly series. According to the method, the whole country is first divided into grid cells depending on the dataset used. For the analyses of mean SAT in the periods since 1951 and 1905, longitude/latitude grid cells of 2.5° by 2.5° and 5.0° by 5.0° are used respectively. The evaluation of the effects of urbanization on the mean SAT trend in a few case regions adopts the 1.0° by 1.0° longitude/latitude grid size due to the use of denser station networks. Temperature anomalies for stations are calculated with 1971–2000 as the base period. An arithmetic average is made of the temperature anomalies of all stations for every grid cell, and an average of all grid cells are finally calculated by using an area-weighted method with the cosines of the mid-latitudes of the grid cells as coefficients of the weights.

With this procedure, national average annual and seasonal (spring, summer, autumn, winter) mean SAT anomaly series for the periods of 1951–2017 and 1905–2017 are obtained. Winter is defined as the three months from December of the previous year to February (DJF), spring from March to May (MAM), summer from June to August (JJA), and autumn from September to November (SON). The annual mean value is the arithmetic average of the monthly averages of the 12 months in a year.

The magnitude and nature of the SAT temperature trend can be indicated by tendency coefficient, rate of change, and difference between the averages of two equally long periods. The tendency coefficient is defined as the correlation coefficient between yearly temperature (temperature anomalies) values and ordinal number of the years. When the tendency coefficient is positive (negative), it indicates that temperature in the analyzed period tends to linearly increase (decrease). It is easier to use the tendency coefficient to assess the statistical significance for individual observation series. The rate of temperature change is obtained by using the least square method to calculate the linear regression coefficient between yearly temperature (temperature anomalies) values and time or ordinal number of the years. Ten times the regression coefficient is called per decadal rate of temperature change or trend of temperature (°C/10yr). Statistical significance of the linear temperature trends is assessed by using T-test method. Serial correlation in temperature data series may significantly affect the estimate of trends and the confidence test (von Storch, 1982; Zhang & Zwiers, 2004). However, there is a controversy about whether to pre-whiten the autocorrelation of original monthly mean temperature data (Bayazit & Onoz, 2007; Yue & Wang, 2002, 2004a, 2004b). Therefore, the serial correlation of original temperature data has not been considered in this study. Further information on the analysis methods can be found in Jones and Moberg (2003), Ren et al. (2005b), and Cao et al. (2016).

Surface Air Temperature Changes

Past 67 Years

During 1951~2017, annual mean SAT in China obviously increased (Figure 2), and the linear rate of change was 0.24°C/10yr, which is statistically significant at the 99% confidence level. The annual mean temperature rose by 1.61°C during the entire period. The temperature increase occurred dominantly after the early to mid-1980s. Before that, average annual mean SAT fluctuated with a small range, and only an insignificant positive trend can be detected; starting from the mid-1980s, however, the temperature has kept rising steadily. Before 1980, the country as a whole was warmer than normal only in 1973; while during the following 37 years, it was warmer than normal in 29 years, with 2007 being the warmest year in the record, when the annual mean SAT anomaly reaches 1.24°C.

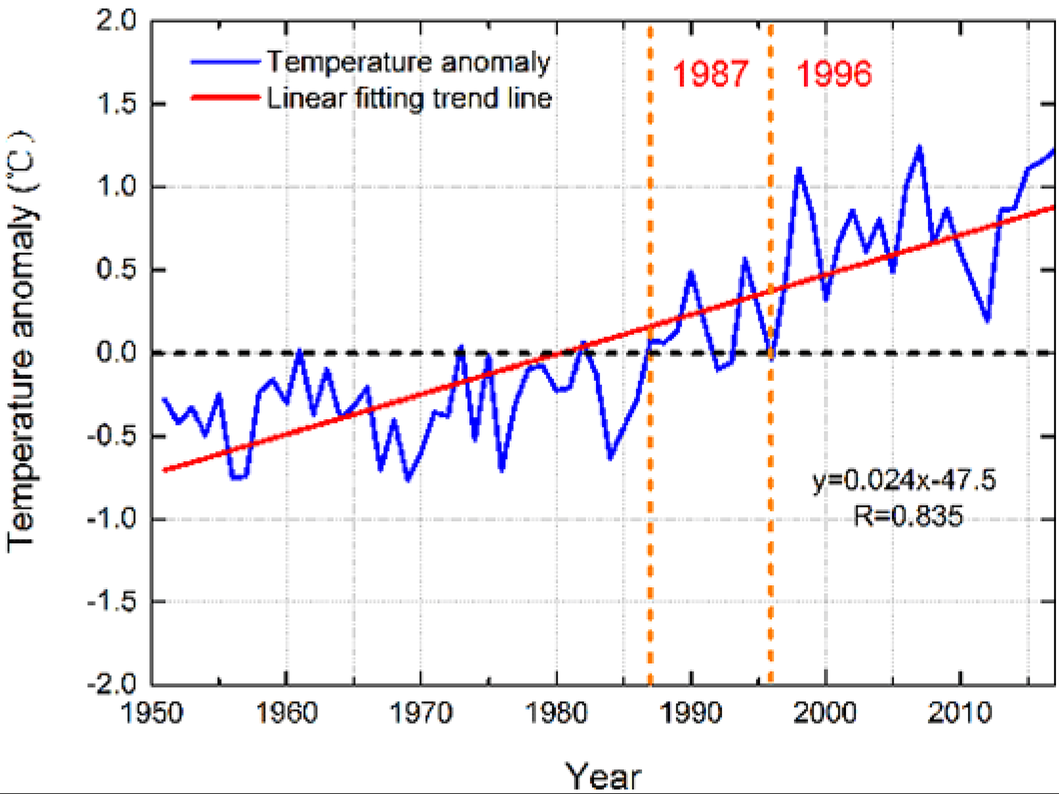

Figure 2. Average annual surface air temperature anomalies over China: 1951–2017.

However, a slowdown of the warming can be seen after 1998 or 2000, with the 2007–2011 experiencing a tremendous drop in temperature. The rising trend during 1998–2017 is insignificant. The slowdown of regional warming in Mainland China has been reported in previous studies (Li et al., 2015; Sun et al., 2017a), and it seems that northeast China and its neighboring regions undergo even a cooling trend after 1998 (Sun et al., 2017b).

Seasonal mean SAT shows upward trends for the period 1951–2017 as well (Figure 3). The warming in winter is statistically significant at the 99% confidence level, with the rate of change reaching 0.34°C/10yr. The warming in spring and autumn is also significant, while summer witnesses the smallest increase in mean SAT, though the warming is still statistically significant at the 99% confidence level. The temperature change in summer and spring is smaller in much of the period analyzed, but it becomes more obvious after the mid-1990s. On the other hand, autumn and winter are more similar in seasonal mean SAT change as both undergo rapid warming from the early to mid-1980s. The largest temperature anomalies occur in 2008 for spring, in 2006 for autumn, and in 2016 and 2017 for summer and winter. It is also visual that the slowdown of seasonal warming in the recent 20 years is more remarkable in autumn and winter (Figure 3c, Figure 3d).

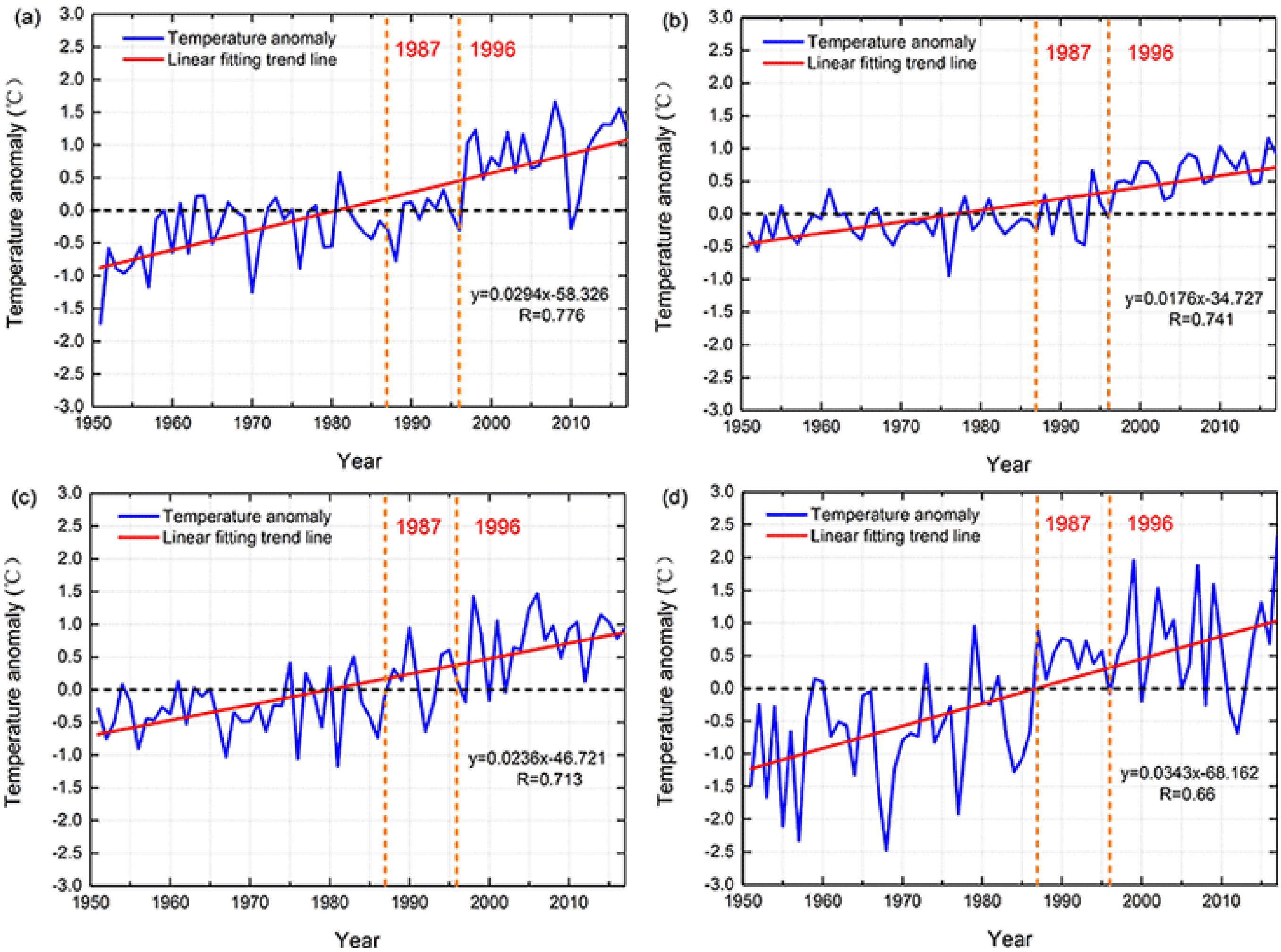

Figure 3. Seasonal mean surface air temperature anomalies over China: 1951–2017 (a) Spring; (b) Summer; (c) Autumn; (d) Winter.

Figure 4 shows the trends of monthly mean SAT during 1951–2017. Evident warming (all statistically significant at the 99% confidence level) occurs for every month, with the first four months (JFMA) and the last two months (ND) undergoing above-average trends and the months (MJJASO) in the warm season below-average trends. February witnesses the largest warming, and August and July experience the smallest increase in monthly mean SAT.

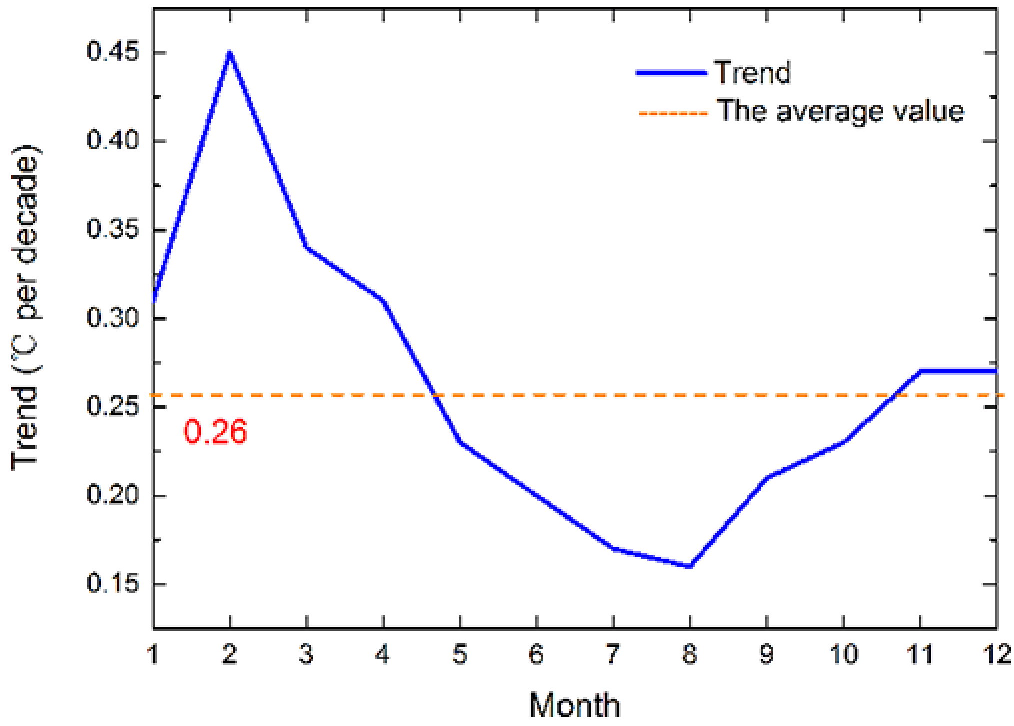

Figure 4. Trends of monthly mean surface air temperature during 1951–2017. Dotted line denotes the average value or trend of annual mean temperature.

Warming in spring and autumn may have led to a lengthening of the growing season. An examination of change of climatologically defined growing season for the period 1961–2000, using daily mean SAT data, shows that it has increased obviously in most areas of the country, especially in the Qinghai-Tibet Plateau (Xu & Ren, 2004). The growing season increased by about six days nationwide but almost 12 days in the Qinghai-Tibet Plateau.

Figures 5 and 6 show spatial distributions of linear trends of annual and seasonal mean SAT for the period 1951–2017. Nationwide, except for the Sichuan Basin and the nearby areas including northern Yunnan-Guizhou Plateau, obvious warming is experienced during the 67 years. The increase in temperature is statistically significant at the 99% confidence level in northern China, the Qinghai-Tibet Plateau, the Hainan Island, southern Yunnan Province, the mid and lower Yangtze River, and the Pearl River Delta, and the trends in the Sichuan Basin and a few of areas in southwestern Yungui Plateau are small and not significant statistically. The largest increase is seen in northwest China, northern Qinghai-Tibet Plateau, Inner Mongolian Autonomous Region, northeast China, northern North China, and the coastal zone of South China (Figure 5).

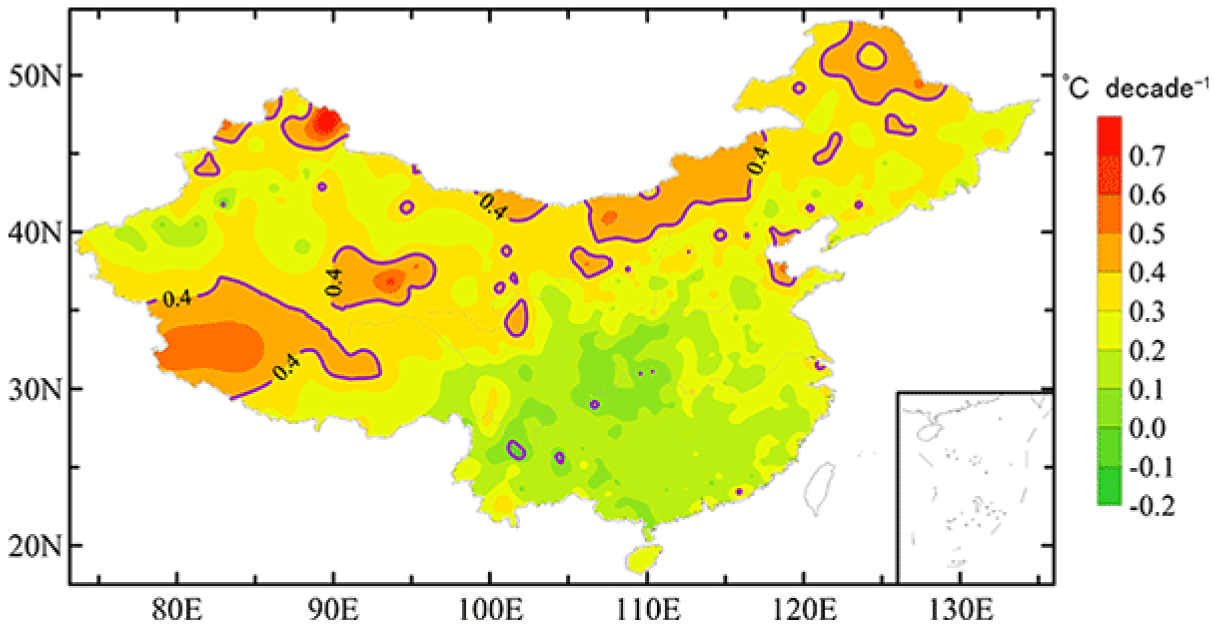

Figure 5. Trends of annual mean surface air temperature over mainland China from 1951 to 2017.

Seasonal mean SAT in north China and the Qinghai-Tibet Plateau increases significantly for all seasons except for summer in north China. Northeast China and Inner Mongolia Autonomous Region also see an evident warming in all seasons except for autumn in northeast China. Seasonal mean SAT in Xinjiang Uygur Autonomous Region of northwest China increases, but a little region of the Tarim Basin of Xinjiang Uygur Autonomous Region witnesses a cooling trend in summer and autumn. Northwestern Qinghai Province undergoes the largest increase in seasonal mean SAT for all seasons except for spring. Although an obvious cooling in summer occurs, the climate in other seasons is getting warmer in the mid and lower Yangtze basin and the southern end of north China. The spring and summer cooling phenomenon in parts of southwest China, including the Sichuan Basin, the Qinling and Daba Mts., and northern Yunnan-Guizhou Plateau (Figure 6), had already been noted (e.g., Chen et al., 1991; Chen & Zhu, 1998; Li, Zhou, Li, & Chen, 1995; Liu et al., 2004), and it still remains when reanalyzed using the homogeneity-adjusted dataset (Hu, Yang, & Wu, 2003; Ren et al., 2005b), though the negative trends are insignificant for most of the stations. The causes for the cooling are under investigation, but it is generally attributed to the combined influence of aerosols and landforms on surface air temperature (Chen & Zhu, 1998; Qian, Leung, Ghan, & Giorgi, 2003, 2006; Ren et al., 2005c).

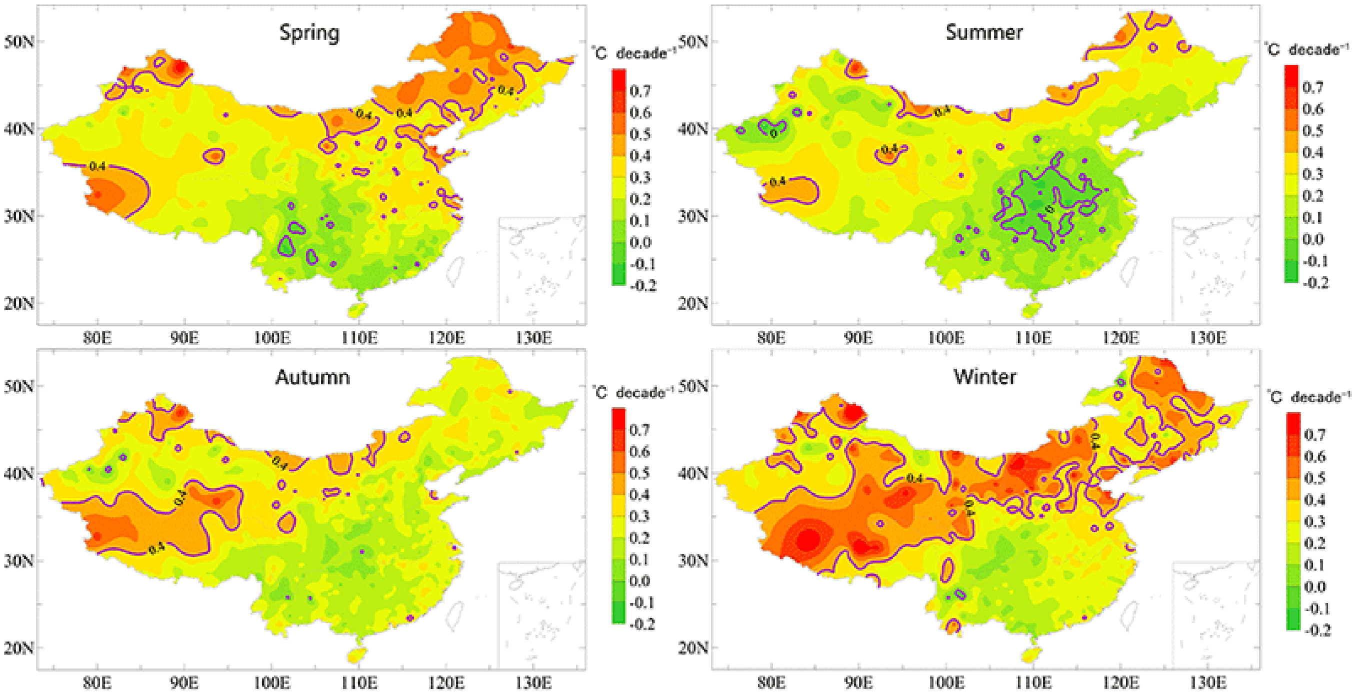

Figure 6. Trends of seasonal mean surface air temperature over mainland China from 1951 to 2017.

Past 113 Years

Figure 7 shows the nation averaged annual mean SAT anomalies for the period 1905–2017. Annual mean SAT rose by 1.38°C, with the linear trend of temperature reaching 0.12°C/10yr, which is statistically significant at the 99% confidence level. The change is slightly larger than the global average temperature increase during the same period (Jones et al., 2012; Lawrimore et al., 2011). Two distinct warm periods, one from the 1930s to 1940s and another after the mid-1980s, can be clearly seen in Figure 5, with the 1940s and 2000s being the two warmest periods on the record. The highest temperature for the entire period analyzed occurred in 2007. As there is an obvious difference between the temperature anomalies of the two warm periods, the warming of Mainland China since 1980s seems anomalous, as it is worldwide or in the northern hemisphere. This result implies that China's 113-year warming may not have been caused by the multi-decadal natural variability. Human activity may have played an important role, although the confidence of the temperature anomalies of the early half of the 20th century is lower due to sparse distribution of observations.

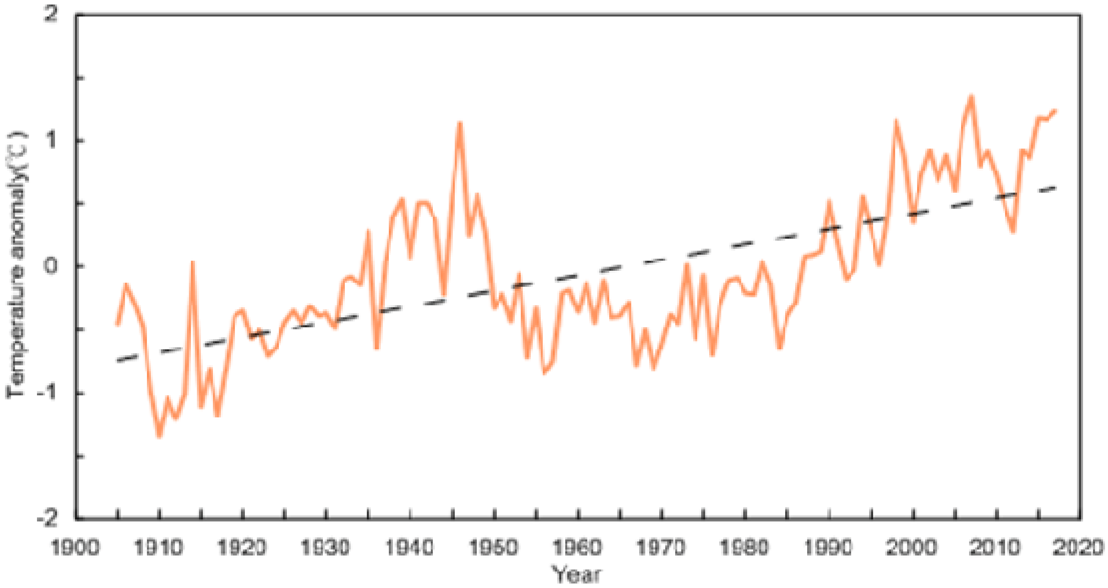

Figure 7. Annual mean surface air temperature anomalies in mainland China: 1905–2017. The solid lines denote temperature anomalies, and the dashed line indicates the linear trend that is significant at the 99% confidence level.

There are some differences between seasonal mean SAT variations during the past 113 years (Figure 8). The linear trends of seasonal mean temperature are estimated to be 1.44°C, 0.89°C, 0.36°C, and 2.04°C, or 0.14°C/10yr, 0.09°C/10yr, 0.04°C/10yr, and 0.20°C/10yr, respectively, for spring, autumn, summer, and winter. The largest positive temperature trends are in winter and spring, and the smallest ones are in summer and autumn, as they are for the period 1951–2017. The warming in spring, autumn, and winter is statistically significant at the 99% confidence level. Although the 1940s and the post-1990 period were two obvious warm stages in terms of annual mean SAT anomalies, the seasonality of temperature changes in the two periods is different, as the largest positive temperature anomaly of 1940s occurred in summer rather than in spring and winter as it did after the 1990s.

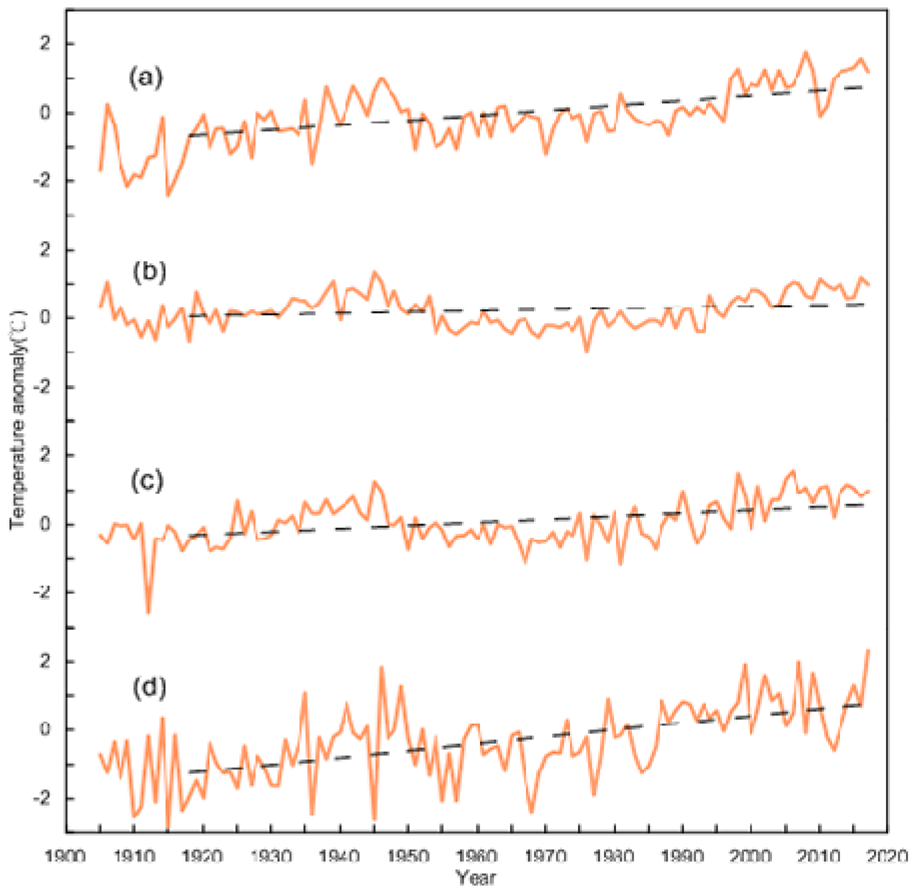

Figure 8. Seasonal mean surface air temperature anomalies in mainland China: 1905–2017. The solid lines denote temperature anomalies, and the dashed lines indicate linear trends that are significant at the 99% confidence level except for summer: (a) spring, (b) summer, (c) autumn, (d) winter.

It is interesting to note that the 113-year temperature series of Mainland China has similarities with the change in average Arctic annual and seasonal mean SAT during 1900–2001 (Polyakov et al., 2002; Bengtsson, Semenov, & Johannessen, 2004; ACIA, 2004). In Arctic land regions from 60° N to 90°N, the annual mean SAT similarly shows two abnormally warm periods in the 1930s–1940s and post-1980s, with the warmest years of the two periods exhibiting an insignificant difference if the recent 15 years are not considered. Furthermore, the seasonality of the temperature variations in Mainland China and the Arctic region is identical as well, in that the warming in both regions occurred in summer for the 1930s–1940s period, but in winter for the post-1980s period. More obvious warming than the global average in summer during 1930s–1940s also occurred in Europe and probably in eastern United States (Kincer, 1933), although the increase in summer temperature in Europe after the mid-1980s is faster than in the earlier warm period in the region (Jones & Moberg, 2003; Polyakov et al., 2002). In comparison with the other long-term mean SAT series of Mainland China, including those by Lin, Yu, and Tang (1995) and Wang et al. (1998, 2002), the positive temperature trend estimated in this paper is generally larger but more or less consistent with those reported more recently by Li et al. (2010) and Wang et al. (2014). Lin, Yu, and Tang (1995) obtained a trend of about 0.03°C/10yr for the 1873–1990 period, and Wang et al. (2002) reported a trend of 0.06°C/10yr for the 1880–2000 period. However, the three surface air temperature series are identical in decadal variations, though the present one shows significantly lower temperature anomalies than the others do during 1910–1940. The more evident warming trend and the lower temperature in the early decades as obtained in this paper could be attributed to the different statistical methods used for calculating monthly mean temperature and the treatment of inhomogeneity of the pre-1950 dataset, and the varied periods analyzed by the different groups (Tang & Ren, 2005).

However, the linear trend of annual mean SAT series of the past century as reported in this paper is much smaller than those obtained by Cao et al. (2013) and Zhao et al. (2014). The difference in temperature trends may have been related to the fact that a smaller dataset only containing 16–32 stations, and the observations mostly located in big cities of eastern China was used by Cao et al. (2013), Zhao et al. (2014), and Li et al. (2018). The discontinuous points existed in the data series, which were mainly induced by relocations of the stations usually from more urban areas to suburban areas, were also adjusted by the authors. The records at the stations may have been significantly affected by urbanization, and the adjustment of the breakpoints in the urban data series may have led to a recovery of urban warming bias (Zhang et al., 2013; Ren et al., 2015). This may have been the major reason why much larger warming trends than our analysis results had been obtained in Cao et al. (2013), Zhao et al. (2014), and Li et al. (2018).

Discussion of Urbanization Effect

A key issue in detection and attribution of climate change is to what extent the increased urban heat island effect has affected the observed trends in global or regional average SAT (Karl, Diaz, & Kukla, 1988; Jones et al., 1990; Ren et al., 2008). Some studies focused on eastern China, but they yielded radically different results in earlier years (Wang, 1990; Jones et al., 1990; Zhao, 1991; Portman, 1993; Li et al., 2004b; Zhou et al., 2004). Later works frequently showed that surface warming recorded at the national stations of Mainland China is partially attributable to the effect of urbanization (e.g., Chu & Ren, 2005; Ren et al., 2007, 2008; Ren & Zhou, 2014; Yang et al., 2013). The effect of urbanization on annual mean SAT trend of the recent 40–50 years as obtained from the national stations, for example, is significant in Shandong, Hubei, Hebei and Gansu Provinces, and Tianjin Municipality (Zhang & Ren, 2005; Chen et al., 2005; Liu et al., 2005; Bai et al., 2006), and also in larger spatial domains including north China (Ren et al., 2008; Zhou & Ren, 2014; He et al., 2013), eastern China (Yang, Hou, & Chen, 2011), southwestern China (Tang, Ren, & Zhou, 2008), and Mainland China as a whole (Zhang et al., 2010; Wang & Ge, 2012; Ren & Zhou, 2014; Ren et al., 2015). This is understandable because most of the national stations are located in or near cities in Mainland China, which have undergone unprecedented growth for almost four decades since the late 1970s' economic and social reform.

North China registers the largest increase in annual mean SAT during the period 1951–2017, as seen in Figure 5. The urbanization effect on annual and seasonal mean SAT trends as recorded at national stations in the region during 1961–2015 was analyzed using a monthly mean SAT dataset of 166 stations and station metadata, referring to the method of Ren et al. (2008). A total of 29 rural stations selected from the 143 reference temperature stations network of Mainland China (Ren et al., 2015) were used as reference sites for estimating the urbanization-induced warming. The 143 reference temperature stations were selected from 2,400 observational stations over the country by taking account of the time of records, the continuity of observations, the settlement populations close to the stations, the relocations of stations, the distance of the observational grounds to the nearby urban center, and the ratio of built-up areas within $12m^2$ centered on stations (Ren et al., 2015). Region-averaged SAT trends of the reference temperature stations (rural stations) and the national stations were compared, and the urban warming for the national stations as a whole and the contribution of the urban warming to the overall warming observed during 1961–2015 were estimated. The analysis was able to show that the increase in annual mean SAT induced by urbanization for the national stations is 0.52°C or 0.10°C/10yr for the period 1961–2015, and the contribution of urbanization to the overall warming as obtained from the nation stations reaches 31.1% (Table 3).

Table 3. Effect of Urbanization on Annual and Seasonal Mean Surface Air Temperature of the National Stations in North China During 1961–2015

	Urban Warming (°C)	Rate of Urban warming (°C/10yr)	Contribution of Urban Warming (%)
Annual	0.52	0.1	31.1
Spring	0.53	0.1	27.0
Summer	0.48	0.09	49.4
Autumn	0.49	0.09	33.1
Winter	0.62	0.11	27.9

The urban warming and the contribution to the overall warming at the national stations of north China are season dependent (Table 3). The largest urban warming occurs in winter, and the smallest urban warming is in summer. However, the largest fractional contribution of urban warming to the overall seasonal mean SAT trends is in summer, reaching 49.4%. The contribution decreases to 33.1% for autumn and to 27% to 28% for winter and spring. Although the largest warming and urban warming occurs in winter and spring, the urban warming makes up a smaller proportion in the overall warming trend in the two seasons. This indicates that the rapid warming in winter and spring in north China during the time period analyzed might have been dominantly by the large-scale background climate change and variability mainly related to the currently identified factors such as anthropogenic CO_2 concentration increase in atmosphere and ocean-atmospheric mode variability.

Analyses for other regions of the country delivered comparable results (e.g., Chen et al., 2005; Chu & Ren, 2005; Zhang & Ren, 2005; Liu et al., 2005; Bai et al., 2006; Tang et al., 2008; Yang et al., 2011; Wang & Ge, 2012; He et al., 2013; Sun et al., 2016). A summary of a few of the regional analysis results is shown in Table 4. All of the case regions see a significant effect of urbanization on annual mean SAT trends recorded from the national stations. The urban warming at the national stations ranges from 0.06°C/10yr to 0.16°C/10yr, and the contribution of the urban warming to overall warming varies from 19% to 75%. The large divergence of the values might result mainly from the differentiated economic growth rates and urbanization processes, the relative locations of the national stations to the built-up areas of cities or towns and the definitions of the “rural stations” used by the different authors. Zhang et al. (2010) and Ren et al. (2015) reported their analysis results for all of the national stations in Mainland China applying the same dataset of 143 reference temperature stations and showed a country-averaged annual urban warming of 0.08°C/10yr, and an urbanization contribution of 27% to the overall increase in SAT, for period 1961–2004.

Table 4. Average Urban Warming and the Fractional Contribution to the Overall Warming for the National Stations (Urban Stations) in Mainland China During Varied Periods Since 1961, as Estimated by a Few of Representative Research Groups Using Urban-Rural Trend Method and Homogenized Temperature Data

	No. of NS	No. of RS	Time Period	Urban Warming (°C/10yr)	Contribution of Urban Warming (%)	Authors and Publication Year
Gansu, P.	23	6	1962–2002	0.06	19	Bai et al. (2006)
Hubei, P.	19	10	1961–2000	0.09	75	Chen et al. (2005)
Shandong, P.	16	5	1961–2000	0.09	27	Zhang & Ren (2005)
Hebei, P.	20	32	1961–2000	0.14	40	Liu et al. (2005)
Beijing, M.	2	6	1961–2000	0.16	71	Chu & Ren (2005)
Tianjin, M.	1	3	1964–2002	0.11	20	Guo et al. (2009)
Anhui, P.	52		1980–2008		36 (urban)	Yang et al. (2013)
SW China	204 (all)	118	1961–2004	0.05	45	Tang et al. (2008)
N. China	282	63	1961–2000	0.11	38	Ren, et al. (2008)
E. China	463 (all)	145	1981–2007	0.08-0.29	21-44 (urban)	Yang et al. (2011)
Jing-Jin-Ji	63		1978-2008	0.13	44	He et al. (2013)
Average				**0.10**	**42**	
Mainland	160	29	1980-2009	0.09	20	Wang & Ge (2012)

	No. of NS	No. of RS	Time Period	Urban Warming (°C/10yr)	Contribution of Urban Warming (%)	Authors and Publication Year
Mainland	614	143	1961-2004	0.08	27	Zhang et al. (2010)

Note: P.=Province; M.=Municipality; N. China=North China; NS=national stations; RS=rural stations. The average is the simple arithmetic mean of all the urban warming and contributions of urban warming of national stations, with those estimated for urban stations excluded.

The dataset of national stations has so far been the basis for constructing national or regional average SAT series. The existence of the urban warming has undoubtedly led to overestimates of the region-averaged SAT trends obtained from the dataset. The national average SAT trends of the period 1951–2017 described in the previous section have, therefore, contained the errors of urbanization effect to a large extent. It is still hard, however, to give an accurate estimate of the effect for the country as a whole for the time being. As the rural or reference stations used in the previous studies could hardly be considered as real baseline observation sites, the urban warming of the national stations and its contribution to the overall warming given in Table 3 and Table 4 should be taken as the minimum estimates. If the analytical results of Mainland China (Zhang et al., 2010) are taken as representative, however, the trend of annual mean SAT in Mainland China during 1951–2017 could be less than 0.18°C/10yr after the urbanization bias is corrected.

The urbanization effect on the annual and seasonal mean SAT records in the first half of the 20th century could be also important. As most of the surface observations at the early time are made in the east with a relatively developed economy, and almost all are located in cities and towns that have been the mega or big cities since the early 20th century, it is likely that there will also be the increased urban heat island effect in the earlier part of the long SAT series. However, it is difficult to accurately assess the urban warming for the early part of the temperature series due to the lack of reference stations. If the 27% urbanization contribution to overall warming could be extended to the whole time period of 113 years, which is highly arguable, the country-averaged annual mean SAT trend would be less than 0.09°C/10yr.

Concluding Remarks

The country-averaged annual mean SAT has increased obviously in the period of 1905–2017. It rose by 1.38°C or 0.12°C/10yr. The change is slightly larger than the global average warming in the same period. In contrast with the global and northern hemisphere averages, the increase in annual mean SAT of China since the early or mid-1980s is not significantly larger than that during the 1930s–1940s period, while the cooling from 1910s to 1920s and from 1950s to 1960s is more evident. Similar to most parts of the world, warming in China mainly occurs in winter and spring in the past century.

In the period 1951–2017, when better observation data became available, annual mean SAT in China increased by 1.61°C or 0.24°C/10yr. The linear trend of temperature is significantly higher than the global and northern hemisphere averages during the same time period. The most significant warming during 1951–2017 occurs in northeast, north, and northwest China and the Qinghai-Tibet Plateau. The coastal regions also register more rapid warming. The higher estimate in annual mean SAT trend for the period since 1950s as compared to the previous analyses has been attributed to the adjustment of inhomogeneities of temperature dataset, which in some extent restores the effect of urbanization on the SAT records (Hansen et al., 1999; Ren et al., 2005b; Zhang et al., 2013).

Warming induced by urbanization near the national stations has not been taken off from the abovementioned temperature trends. Increased urban heat island effect significantly affects the mean SAT records of the period since 1961 at most national stations in a few case areas and the country as a whole investigated so far. The mean SAT data from the national stations have been used for constructing national or regional average SAT series. In north China, which witnesses the most significant warming during the 1961–2004 period, for example, the annual mean SAT increase induced by urbanization at the national stations accounts for 38% of the overall warming recorded. Case studies for a few other regions give a range of 19%–75% for the contributions of urbanization effect to the overall warming of the national stations, and the study for Mainland China on a whole shows a 27% urbanization contribution the annual mean warming for the period 1961–2004.

Supposing that the estimate of the urbanization effect in Mainland China were representative of the entire 67 years and 113 years, the national average annual mean SAT trend would stand below 0.18°C/10yr for period 1951~2017, and 0.09°C/10yr for the period 1905–2017, if the bias from urban warming were to be removed.

The results obtained show that the construction of historical SAT series can be further improved by applying more thorough and homogenous observation data. They also indicate that the urbanization effect on mean SAT trend of the recent decades or the last century is large on regional scales, and it should not be overlooked in constructing large-scale land mean SAT series and in detecting climate change. The acknowledgment of the urbanization effect does not necessarily mean denial of the fact of surface climate warming, but it has indeed weakened the baseline temperature increase in Mainland China to a large extent.

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Further Reading

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