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An Overview of Mainland China Temperature Change Research

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ABSTRACT

There has been significant effort devoted to investigating long-term trends in land surface air temperature over mainland China by Chinese scientists over the past 50 years, and much progress has been made in understanding dynamics of the changes. This review highlights research conducted by early Chinese climatologists, and particularly Professor Shaowu Wang from Peking University, with special focus on systematic work that has been conducted since the mid to late 1970s. We also discuss major issues that remain unresolved in past and current studies. The most recent analyses indicate that the country-average annual mean surface air temperature rose by 1.12°C over the past 115 years (1901–2015), with a rate of increase of about 0.10°C decade^{-1}. Temperatures have risen more rapidly since the 1950s, with the rate of increase of more than 0.25°C decade^{-1}. However, the recent increase in temperatures is in large part due to contamination by systematically biased data. These data are influenced by unprecedented urbanization in China, with a contribution of urbanization to the overall increase of annual mean temperatures in mainland China of about one third over the past half a century. If the bias is corrected, the rate of increase for the country-average annual mean surface air temperature is 0.17°C decade^{-1} over the last 50–60 years, which is approximately the same as global and Northern Hemispheric averages in recent decades. Future efforts should be focused towards the recovery and digitization of early-year observational records, the homogenization of observational data, the evaluation and adjustment of urbanization bias in temperature data series from urban stations, the analysis of extreme temperatures over longer periods including the first half of the 20th century, and the investigation of the observed surface air temperature change mechanisms in mainland China.

Key words: observational data, surface air temperature, mainland China, modern time, climate change, urbanization effect, climate warming

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1. Introduction

Global and sub-continental surface air temperature change is one of the core issues of contemporary climate change and has garnered significant interest from climate scientists. Chinese scholars realized in as early as the 1960s that global and Chinese climates have undergone significant changes (Zhu, 1962), and presented preliminary analyses regarding temperature and precipitation trends. From the late 1970s to the early 1980s, average global surface air temperature increased once again from the relatively low period during the early 1950s to the mid 1970s, and the global climate exhibited accelerated warming. Thus, monitoring and detection of land surface air temperature and sea surface temperature change began to receive further attention from Chinese and global academic institutions.

Professor Shaowu Wang, an outstanding Chinese climatologist, was one of the earliest scholars that studied on Chinese temperature change. Beginning in the early 1960s, he analyzed temperature observations over the previous 87 years at Xujiahui (Zikawei) Station in Shanghai, and found that annual mean temperature significantly increased after 1920, peaking in the 1940s, and

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then declined (Wang, 1962). Although the work is localized to a single site, it was of great significance in understanding local temperature change and evoked public interest in long-term climate change. Wang also conducted a systematic study of decadal-scale national temperature change and found that temperatures began to rise in the 1920s, peaked in the 1940s, and declined significantly in the 1950s. Following these results, he suggested that the cause of climate drift after the 1950s was due to changes in sea level pressure and the atmospheric center of action (Wang et al., 1963). Atmospheric centers of action are perennially or seasonally stable high and low pressure systems that affect large-scale weather and climate change. Decadal variations in average national temperatures have been confirmed by later research and Wang's conclusions appear to be generally supported.

Chinese scientific and technological research entered a new stage of rapid development following 1978, which coincides with the period when global average surface temperatures began to rise significantly and increased attention was given to global warming by academia. Professor Wang and others became the leaders of climate change science once again in this new era of climate research. This paper primarily reviews research progress regarding land surface air temperature changes over mainland China since the middle and late 1970s and highlights the perseverance and contribution to the scientific issue by Chinese scholars, and particularly Professor Shaowu Wang.

Here, we discuss changes in surface air temperature over mainland China in the modern era, with particular reference to multi-decadal- to century-scale variations and long-term trends of the annual mean land surface air temperature over mainland China, covering the modern instrumental observation period. Changes of surface air temperature in the historical period and the geological period, interannual and interdecadal fluctuations of modern land surface air temperature, changes in modern upper atmosphere temperature, and causes of modern land surface air temperature change and possible future temperature trends are not considered in the present review.

2. Temperature changes over the past 100 years

Studies of mainland China surface air temperature changes using long instrumental observation data started in the mid 1970s. Jiacheng Zhang, Xiangong Zhang, Jijia Zhang, Qipu Tu, and others conducted preliminary analyses on the observations and potential reasons for surface air temperature change over the past few decades to 100 years. Zhang et al. (1974) analyzed global and Chinese temperature changes on different timescales, and concluded that climatic variations on the greater than decadal scale were similar in China and globally. Further, their analyses indicated that global high latitude areas began cooling during the 1940s, as was also apparent in China. Zhang (1978) confirmed that Chinese temperature change in the 20th century was consistent with global temperature change by using temperature grade data. Moreover, they identified the 1940s as a period with relatively high temperatures and showed that the global and Chinese annual mean temperatures dropped 0.3 and 0.4–0.8°C, respectively, from then until the early 1970s. Zhang et al. (1979) analyzed the primary features of mainland China surface air temperature fluctuation on the greater than decadal scales by plotting temperature anomaly cumulative curves for representative months in four seasons from eight stations that had long-term observational data. The results showed that amplitude and period in East China were larger and longer than in West China, but the smallest amplitude existed in coastal areas of South China. They also suggested that long-term fluctuation in the Northern Hemisphere is related to large-scale atmospheric circulation anomalies.

Zhang and Li (1982) used monthly mean temperature data from 137 stations to construct China surface air temperature series and analyzed long-term surface air temperature variation throughout the previous century. In their study, the area-average temperatures were calculated by five to seven representative stations selected from each of seven regions in mainland China: Northeast China, North China, Yangtze River, South China, Southwest China, Northwest China, and the Xinjiang Region. The study represented the first country-average surface air temperature grade series with almost 100 years of data for mainland China. The results indicated that mean surface air temperature change during 1910–1979 in China was consistent with that in the Northern Hemisphere in general, which exhibited warming in the early 20th century and rapid cooling after the 1940s, with the most obvious cooling occurring in summer and autumn. However, the analyses were conducted in 1979 and did not capture the significant nationwide climate warming that occurred in the several years that followed, and particularly after the mid 1980s. Further, the country-average series lacked data from Xinjiang and Tibet in the first half of 20th century, which resulted in a potential underrepresentation of country-average warming trends.

Zhang et al. (1982) and Zhang (1983) analyzed the spatial variability and propagation feature of global surface temperatures in the late 1960s–1970s. These studies indicated a spreading phenomenon from west to east in the temperature anomaly centers of the Northern Hemisphere westerly zone, while tropical temperatures progressively changed in the east to west direction. Further, these studies linked abnormal temperatures of China and northeastern China in the 1970s to global-scale temperature changes and indicated that the cold or warm summers in northeastern China were consistent with global climate abnormalities. These studies were not aimed at the long-term region-specific temperature trends, but did aid in understanding the spatial patterns and mechanisms of surface temperature variations in China.

Tu (1984) analyzed the annual and seasonal mean temperatures of China's 42 observation stations in the time period encompassing 1881–1981 by using principal component analysis methods. Mainland China was divided into five regions based on the interannual variability of temperature. The first principal component of annual and seasonal average temperatures of most areas was consistent with the average temperature change in the Northern Hemisphere, with the exception of Northeast China and northern Xinjiang. From the beginning of the 20th century to around 1945 and again from the 1970s to present day, there were two obvious warming periods, and a mild cool period in the interim. In part due to 3-yr additional data compared to Zhang and Li (1982) as well as the principal component signal extraction method, this work was the first to discover the phenomenon of Chinese re-warming after the mid- to late 1970s. Importantly, the work indicated climate warming in the new era and the consistency of the rising temperature trend with the Northern Hemisphere.

In the early 1990s, Shaowu Wang, Yihui Ding, Xuecun Lin, and colleagues systematically evaluated changes of land surface air temperature in mainland China over nearly 100 years, which represented a significant step forward in the study of Chinese long-term climate change.

Wang (1990) analyzed temperature change in eastern China over the previous century and compared it with average temperature change in the Northern Hemisphere and the whole world. These analyses were based on temperature grade data during 1910–1988, annual mean temperature data of Harbin, Beijing, Shanghai, and Guangzhou that were interpolated to the stations from nearby records during 1880–1988, and the eastern China decadal mean temperature anomaly data reconstructed from historical documents. This time series mainly reflected long-term temperature changes of the eastern monsoon region due to the lack of data in the western non-monsoon region, particularly because Xinjiang and Tibet were not included prior to 1950. This work confirmed the large-scale regional temperature rises in China beginning in the 1920s, peaking in the 1920s–1940s, declining afterwards, and also that the northeast and coastal areas of China began warming again in the 1980s. Compared to global average temperature anomaly series, eastern China exhibited a more obvious cooling period during 1950s–1970s. The warming trend lagged behind global trends in the mid to late 1970s, indicating that China's climate warming was generally consistent with global averages, but there were Chinese-specific particularities.

Tang and Lin (1992) were the first to use monthly mean temperature data from a high-density network of observation stations (716 stations) and applied the data to estimating national land surface air temperature time series and its trends from 1921 to 1990. The results suggested that Chinese cooling during the 1940s–1960s was more apparent than that of the Northern Hemisphere, but the warming trends of China in the 1980s were weaker than the Northern Hemisphere, which partially confirmed the conclusions of Wang et al. (1990).

Regression analyses were performed by Ren and Zhou (1994) using 11 stations (including rural plus urban) containing recent observations and four stations (urban only) with longer and earlier records to construct and analyze land surface air temperature anomaly time series for the Liaodong Peninsula in the 20th century. Linear relationships between the two groups for the period 1964–1988 were used to reconstruct annual and seasonal mean temperature anomalies for the whole region over 1905–1988. This approach largely eliminated the impact of urbanization on annual and winter mean air temperature trends, and is one of the first efforts to eliminate urbanization bias on average regional long-term temperature data in the 20th century.

Ding and Dai (1994) systematically reviewed the main findings of temperature change over the previous century in China and highlighted that Chinese surface air temperature change was approximately similar to Northern Hemisphere averages. There were differences, however, with the highest Chinese temperatures appearing in the 1940s rather than in the 1980s and later years, and a cooling trend that had existed in Southwest China since the 1950s. Annual warming in mainland China mainly occurred in northeastern, northwestern, and northern regions, and the country-average surface temperature appeared to have two shifts in approximately the last 100 years, in 1919 and 1952. Further, it was noted that urbanization may have an impact on China's surface air temperature observations and the current estimate results should be adjusted appropriately. The country average surface air temperature change did not exceed the range of natural climatic variability, and it was not certain at the time that this climate change was caused by human activity. This comprehensive review accurately summed up the scientific understanding of that time for the previous century's surface air temperature change.

In the late 1990s, Chinese scholars began to pay more attention to the previous century's surface air temperature changes, coinciding with the acceleration of global and mainland China warming as well as increased focus on climate change by the international community. Shi et al. (1995) used the EOF method to interpolate and analyze monthly mean temperature data from 28 stations in China covering the previous 100 years, and showed that Chinese temperature change exhibited obvious regional differences. Warming was most obvious in Northwest China, Northeast China, and northern parts of North China, whereas warming trends were weak south of the Yellow River. Lin et al. (1995) used the monthly mean temperature records from 711 stations of China (spanning 1873 to 1990) in order to evaluate the annual mean temperature trends for the whole country and different regions. This analysis represented the longest national and regional temperature trend estimations (at the time) by using historical observation data from a high-density station network.

Wang et al. (1998) analyzed temperature change trends in China and globally over nearly 100 years by applying various data and by dividing China into 10 regions. The annual mean temperature anomaly data for China and the 10 regions were obtained for 1880–1996 based on proxy data (ice cores, historical documents, and tree rings) to interpolate data for the areas where instrumental data were lacking. The spatial coverage of the data was greatly improved due to the use of proxy data for Xinjiang and the Tibetan Plateau, which solved the problem caused by spatial data heterogeneity prior to the 1950s. This analysis was the first to provide long-term Chinese temperature series covering the whole country with uniform variance by use of the area weighted average method. The results indicated that the rate of increase for the annual mean surface air temperature was 0.04°C decade^{-1} from 1880–1996. This rate was significantly higher than the previous estimated value, and its decadal variation was more similar to global or Northern Hemisphere averages. Qian and Zhu (2001) used the temperature data of Wang et al. (1998) to further analyze climate change characteristics, and particularly, spatial differences among different Chinese regions. Later, Wang and Dong (2002) and Wang et al. (2005) updated this series, and found that the national average surface temperature increased at a rate of 0.06°C decade^{-1} during 1880–2002, which was similar to the average global warming trend. The results of these studies were widely used in later analyses in the *Assessment Report of Climate and Environment Change* in China, and the *National Assessment Report on Climate Change* (Qin, 2002; Qin et al., 2005; Committee on China's National Assessment Report on Climate Change, 2007).

Chen et al. (1994) used measured data to establish a regional mean surface air temperature series in eastern China following the 1920s and discussed the relationship between air temperature change and monsoon circulation variation. Later, Chen et al. (2004) updated the mean temperature series for the eastern region (east of 100°E) from 1920 to 2002 by including data from the national reference climate stations and the national basic meteorological stations. This series indicated that the annual mean temperature of the warmest year (1998) or the 5-yr running mean temperature of the 1990s in the eastern region of China was almost at, or slightly higher, than the annual mean temperature of the second warmest year (1946) or the 5-yr running mean temperature of the 1940s.

Since the 21st century, China's climate change research has garnered significant attention from government and scientific communities, and surface air temperature change research in modern China has entered an active new stage. Compared to previous studies, research since 2000 mainly has been focused on: 1) the quality of long-range surface observed data, particularly data inhomogeneities, and the addition of high-density and long-term data; 2) systematical evaluation of the urbanization bias in regional and national surface air temperature data series; and 3) comprehensive and integrated analyses on long-term variation characteristics of extreme weather and climate events.

Tang and Ren (2005) gave preliminary consideration to the temporal inhomogeneity of long-term series observations in the 20th century, by applying the mean values of maximum and minimum temperatures as monthly and annual mean values. This approach avoided the discontinuity caused by using observation records at different times of a day to calculate averages, and was also consistent with the standard calculation methods of international monthly and annual mean temperatures. The study used the highest-density observational network data available at that time, and region averages were assessed by using an area-weighted average method over a grid box, which is also in accordance with international practice (Jones et al., 1990). Later, Tang et al. (2009) performed further quality control and interpolation of pre-

1950 data and the original series was updated with data from 291 stations, which provided more continuous observation records and more uniform spatial distribution. However, some problems still existed in the time series data. For example, some stations had incomplete records despite interpolation of data before 1950, inhomogeneity of the series due to station relocation was not corrected, the western region still lacked early data, and urbanization bias had not been properly considered. However, the country average surface air temperature series has been widely used, and has also been used in each of the previous national assessment reports on climate change (Committee on China's National Assessment Report on Climate Change, 2007, 2011; National Climate Center of China Meteorological Administration, 2016).

Figure 1 shows curves of the annual mean surface air temperature anomaly series of mainland China that have been updated by Tang and Ren (2005) and Tang et al. (2009) (red) and Wang et al. (1998) (blue). Based on the analysis of Tang and Ren (2005) and Tang et al. (2009), the country-average annual mean surface temperature increased significantly in mainland China during the period 1901–2015, which is similar to the results previously generated with various methods and data. The temperature variation characteristics on the interannual and decadal scales are prominent. There were two significantly warmer stages between the 1930s and 1940s and again after the mid to late 1980s, but the degree of warming in the latter was significantly higher than the former. Over 115 years, the country-average annual mean surface air temperature linearly increased by 1.12°C, and the average rate of warming was about 0.10°C decade^{-1}. The surface air temperature anomaly in 2015 was 1.17°C (relative to the 1971–2000 average), which was the second warmest year after 2007 since 1901, and was very close to 1998, the first warmest year. The annual mean surface air temperature anomaly series updated from Wang et al. (1998) showed a slightly smaller warming trend in mainland China during the same time period (Fig. 1 and Table 1).

Recently, Cao et al. (2013) used data from 16 stations with relatively complete records in eastern China to construct the annual mean temperature anomaly series (Cao et al., 2013; Wang et al., 2014; Zhao et al., 2014). They examined and partially corrected the data for inhomogeneities caused by station relocation. This series indicated a greater warming trend over the previous hundred years, with a warming magnitude of 1.52°C for 1909–2010 and an average warming rate of about 0.15°C decade^{-1} (Fig. 1), which were higher than previous estimates by other groups. This higher warming trend may be primarily related to the recovery of urbanization effect in the single-station series after homogenization (Zhang et al., 2014), and may also be associated with having fewer number of stations used. Moreover, the time series was mainly focused on data for eastern and central cities of China.

Li et al. (2010a) constructed country-average annual and seasonal mean temperature anomaly series beginning in 1900 using homogenized data from the national reference stations and national basic meteorological stations, and also long series of observational data from a few neighboring countries. Li et al. (2010a) and Du et al.

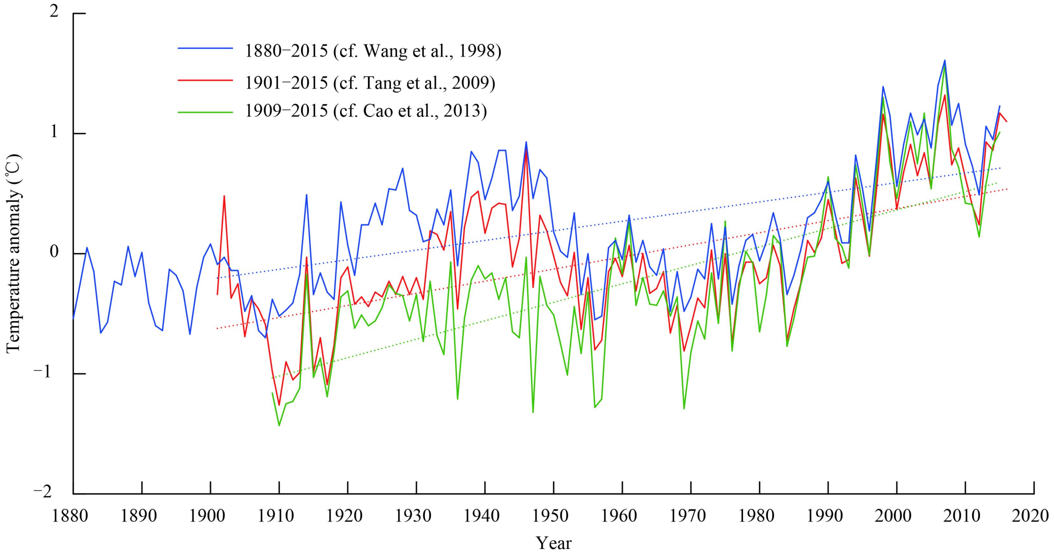

Fig. 1. Changes in country-averaged annual mean surface air temperature anomalies over mainland China during 1901–2015 [relative to the 1971–2000 average; updated from Wang et al. (1998), Tang and Ren (2005), Tang et al. (2009), Committee on China's National Assessment Report on Climate Change (2015), and Cao et al. (2013)].

Table 1. Linear trends of annual mean land surface air temperature (°C decade^{-1}) for mainland China during 1901–2015

Temperature series	Data used	Procedure	Study area	Trend*
Tang and Ren, 2005; Tang et al., 2009	291 stations	5° × 5° grid, area-weighted average	Mainland China	0.10
Wang et al., 1998	Observations plus proxy data, total 50 sites	10 sub-regions, area-weighted average	Mainland China	0.08
Cao et al., 2013	16 stations	Simply arithmetical average	East China	0.15 (1909–2015)
Li et al., 2010a	740 stations plus stations from neighboring countries	5° × 5° grid, area-weighted average	Mainland China	0.12 (1900–2015)

* The trends are significant at the 95% confidence level.

(2012) further estimated and analyzed errors in the China average surface air temperature series. Liang and Chen (2015) analyzed multi-temporal scale temperature changes in the past 139 years in Southeast China, with particular emphasis on the significant contribution of rising low-frequency component of annual mean temperature variability to the recent warming trend in the region.

Table 1 compares the data and methods used and regional ranges represented by the average temperature series from Wang et al. (1998), Tang and Ren (2005), Tang et al. (2009), Li et al. (2010a), and Cao et al. (2013), in addition to the annual mean temperature trends for mainland China or eastern China, covering the period of 1901–2015 based on respective data and method. The warming trends of each series are quite different over roughly the same time period (Table 1). Eastern China had the largest warming trend as estimated by Cao et al. (2013), Li et al. (2010a) reported the second highest warming trend for the country as a whole, while the average warming estimate from Wang et al. (1998) for whole mainland China was the smallest. The trend estimates from Tang and Ren (2005) and Tang et al. (2009) were intermediate.

The annual mean temperature change trends in mainland China were generally between 0.08 and 0.12°C decade^{-1} during the period 1901–2015 (Wang et al., 1998; Tang and Ren, 2005; Tang et al., 2009; Li et al., 2010a). This range is closer to global land annual mean temperature changes during 1901–2014 (Sun et al., 2016), according to the recently developed global land surface air temperature dataset (GLSAT) by the China Meteorological Administration (CMA), and the estimates of global land temperature change according to the CRUTEM4.4.0.0 data, but is slightly lower than the result based on GHCN-V3.2.0 (IPCC, 2013, Table 2). However, the annual mean temperature trends based on homogenized data from 16 stations in eastern China over 1909–2015 (Cao et al., 2013) are much larger than that of any global land temperature data series.

3. Temperature changes over the past half a century

The climate observational network in mainland China is not perfect prior to 1951, and data gaps are a serious problem. Consequently, there is large uncertainty in estimating long-term trends and changes for surface air temperatures covering the past 100 years. On the other hand, warming has become more apparent since the middle of the 20th century, and particularly after the late 1970s. Therefore, many researchers have turned to analyze the high-density and high-quality observational network records of recent decades in order to better understand detailed spatial and temporal structure features in modern surface temperature change in mainland China.

Zhang and Fang (1988) used observational records from 1951–1985 to analyze spatially-specific differentiation characteristics of surface air temperature variations. They found that regional temperature changes are consistent with global observations with increased warming at high latitudes and less warming at lower latitudes. Moreover, they also indicated spatial differences of temperature variations in the eastern, central, and western regions, which may be related to regional differences in monsoon circulation variation and the influence of large terrain features on the atmospheric circulation.

Li et al. (1990) used observational data from 160 stations to analyze Chinese temperature trends and its tem-

Table 2. Linear trends of annual mean land surface air temperature (°C decade^{-1}) for mainland China and the global lands during 1901–2014 (global) and 1901–2015 (mainland China). Updated from IPCC (2013) and Sun et al. (2016) for global land average, and Wang et al. (1998), Tang et al. (2009), and Li et al. (2010a) for mainland China average

Extent	GHCN-V3.2.0	CRUTEM4.4.0.0	CMA GLSAT-V1.0
Global land	0.11*	0.10*	0.10*
Mainland China		0.08–0.12*	

* The trends are significant at the 95% confidence level.

poral and spatial characteristics from 1951 to 1988. Their analyses showed that annual mean temperature rose during 1951–1988 with an increase of 0.2°C in the 1980s relative to the 1950s. The surface warming trend rose with latitude increases, and warming in the winter and autumn was more obvious, while summer mean temperature change was very small and even exhibited a cooling trend. Most of mainland China displays characteristic winter warming and summer cooling. Lin and Yu (1990) analyzed the annual mean temperature trends over the past 40 years using data from 160 national reference climate stations. Their analyses indicated that temperature increased at a rate of 0.04°C decade^{-1} from 1951 to 1989, with the highest rates in Northeast and North China. In addition, the annual mean temperature did not increase but showed a decreasing trend in the Yangtze River and southwestern parts of the country. This work suggested the particularity of surface air temperature changes in the Yangtze River and southwestern regions for the first time.

Chen et al. (1991) analyzed land surface climate change characteristics over mainland China over more than 40 years and discussed the spatial difference of temperature trends by using consecutive observational data from the higher density network of stations. They found that climate warming only occurred in Northeast China, North China, and Northwest China. In addition, they showed that there was a cooling area south of 35°N, north of the Nanling Range, and east of the Tibetan Plateau, with cold centers in Sichuan, southern Shanxi, and northern Yunnan. Later, Chen et al. (1998) used data from over 400 sites comprising the higher density and relatively uniformly spatial distributed dataset to analyze annual and seasonal mean land surface air temperature trends between 1951 and 1995. In order to decrease the influence of urban heat island effects, the authors removed the records of 27 provincial capital stations and Beijing and Tianjin stations when calculating the mean temperature series and linear trends. The analysis confirmed the results of Chen et al. (1991), which suggested regional differences in temperature changes. It also showed that the country-average annual mean temperatures began to significantly rise beginning in 1985.

Zhu (1992) discussed the influence of an area weighted average on temperature trend estimates, and obtained the estimate of annual mean temperature trends for mainland China from 1951 to 1989 based on the monthly mean temperature data of 160 stations. They also compared that with annual mean temperature changes of the Northern Hemisphere. Song (1994) used the pentad mean land surface air temperature data of 336 stations from mainland China to analyze the spatial and temporal temperature dynamics over 40 years. He indicated that there was a significant difference in air temperature interannual variability and long-term trends between different regions and different seasons, while the annual and winter mean air temperatures increased as a whole.

Zhai and Ren (1997) used observational data covering the period 1951–1990 after removing observational records from potentially relocated stations and the data from big cities (more than 500 thousand people). They analyzed the spatial and temporal variation dynamics of the maximum and minimum temperatures, and diurnal temperature range (DTR) in China, showing that maximum temperatures were generally increasing west of 95°E and north of the Yellow River, but they were declining in the south of the Yellow River. Minimum temperatures were generally increasing over mainland China and this increase was more significant in the north. Overall, the annual mean DTR in China exhibited a significant decreasing trend. It was suggested that the significant increase in minimum temperatures reflected the role of sustained and strengthened greenhouse effects in the atmosphere, and maximum temperature change was associated with sunshine and atmospheric moisture conditions. They suggested that removing the observational data with the possibility of station relocations increased the homogeneity of data to some extent and discarding big city stations eliminated warming biases dues to the increased urban heat island effect.

Hu et al. (2003) analyzed the land surface air temperature change in China using data from 160 stations and found significant warming trends during 1951–2000 and land surface air temperature decreased in central China. Qian and Lin (2004) used daily observational data from 498 stations to analyze features of long-term land surface air temperature changes from 1961 to 2000. They found that although there were regional and seasonal differences, each temperature index confirmed that it was warming in northern China and DTR experienced a significant decreasing trend over mainland China. The long-term air temperature index change was suggested to be related to increased precipitation in the Yangtze River basin and decreased precipitation in the Yellow River basin. However, it was probably associated with urbanization and aerosol emission effects. A significantly decreased DTR trend over mainland China had been supported by Hua et al. (2004), who found that annual mean DTR in different regions of mainland China, and particularly in the east region. By analyzing surface air temperature changes of China based on a daily climate dataset of 305 stations for 1955–2000, Liu et al. (2004) also reported an obvious decreasing trend of annual mean DTR due to the large increase in minimum temperature and a slight decrease in maximum temperature.

Wang et al. (2004) used data from 740 national reference climate stations and national basic meteorological stations to examine long-term change characteristics in the basic variables of surface climate and provided new insights on land surface air temperature trends. Their results suggested that the annual mean surface air temperature rose in almost every region, except for a decreasing trend in the middle-lower reaches of the Yangtze River in summer. Additionally, there was a cooling trend in spring and in the middle reaches of the Yangtze River over the whole year, but the cooling phenomenon in the southwest region became less significant. Their results also indicated a warming center in the northeastern region of the Tibetan Plateau, but its reliability must be confirmed due to poor data coverage. This study was the first to indicate that the cooling trend in Southwest China observed previously had been reversed by the 1990s.

Beginning in 2005, homogenized datasets obtained by different methods were used in the analyses of land surface air temperature changes over mainland China (Li et al., 2004; Ren et al., 2005a; Yan and Jones, 2008; Li and Yan, 2009; Li et al., 2016). Importantly, the discontinuity of historical observational data due to man-made factors, such as relocation of stations and instrument replacement, has been adjusted to some extent, which represents important progress over earlier research (Ding and Ren, 2008).

Ren et al. (2005a, b) used monthly mean temperature data from 740 stations across mainland China that were quality controlled and adjusted for inhomogeneity to analyze spatial and temporal characteristics of annual and seasonal mean surface air temperature changes between 1951 and 2004. Their results indicated that annual mean surface air temperature trends were much higher than global or Northern Hemisphere averages for the same time period. The warming rate was about 0.25°C decade^{-1}, and country-wide warming mainly occurred after the mid 1980s. This study was the first to use homogenized monthly surface air temperature data to analyze large-scale climate change in China and confirmed that surface air temperature changes exhibited seasonal and spatial dynamics, which supported previous research results. However, it was also noted that warming is not only highly significant in winter, spring, and autumn, but also in summer, with a seasonal mean warming rate of about 0.15°C decade^{-1}, which was mainly caused by a succession of abnormally hot summers after the 1990s. After using homogenized data, the systematic bias due to urbanization effects was found to obviously remain in the country-average annual and seasonal mean temperature anomaly series based on national climate observational data, and the bias had to be further evaluated and corrected.

Tang et al. (2005) compared the east-west difference of surface air temperature changes for the period 1951–2002, finding that annual mean temperatures increased at a rate of 0.26°C decade^{-1} in the east, and at a rate of 0.18°C decade^{-1} in the west. The increasing trends of spring and winter mean temperatures were significantly larger in the east than those in the west, but the warming trends in summer and autumn were lower in eastern China than those in the western region. Based on data from 160 stations, Huang and Hu (2006) analyzed characteristics of Chinese winter mean temperature changes during 1951–2004. Their results indicated that early-winter and late-winter mean temperature changes were significantly different. In particular, early-winter warming trends in southern China were small, but late-winter warming was more significant. In contrast, early- and late-winter warming trends in northern China were both significant with late-winter seeing a very large and significant warming over the previous decades.

Cao et al. (2016) used homogenized data collected from 2400 stations from 1960 to 2014 to analyze annual and seasonal mean temperature trends. They found that the rate of increase of the annual mean maximum temperature was 0.22°C decade^{-1}, while the rate of increase of the annual mean temperature was 0.38°C decade^{-1}. These estimates were larger than those that had been reported previously. These higher estimates of trends were unexpected because the 2400 stations included a higher proportion of weather stations located in small cities, towns, and villages. The rate of temperature increase should be lower than the estimates obtained based on datasets from 700 stations. Possible reasons for this larger estimation was that the starting year of the data was later, the earlier section of the data series contained the relatively cold period of the 1960s, and also the data were updated to 2014 with the later section of the series including more warm years. In addition, homogenization processing, aimed at correcting the discontinuous records caused by relocations of stations from urban to rural areas, possibly restored the urbanization bias to a greater extent (Zhang et al., 2014; Ren et al., 2015).

Ren et al. (2016) analyzed the spatial and temporal characteristics of surface air temperature change in mainland China by using hourly data from 1973 to 2011. They found that the country-average annual mean temperature rose quickly at night until 1992, and elevated rapidly around midnight, reaching a peak increase rate of 0.27°C decade^{-1}. However, stronger warming occurred in the daytime during the time period 1992–2011, and the fastest temperature increases occurred in the later afternoon with a rate of increase of 0.46°C decade^{-1}. In addition, spring early afternoons replaced winter midnights as the season and time with the most rapid increase rate. The annual warming during 1973–1992 was higher in the northeast region, whereas the southwest, which had previously experienced cooling trends, became the faster warming region during 1992–2011. There were various possible reasons behind the observed trends in surface air temperature, and seasonal and regional differences of temperature changes, but the authors suggested that solar radiation, cloud cover, aerosol, and urbanization around the stations, among other factors, may have played a role.

Recently, Li et al. (2015) reported the phenomenon of warming slowdown in mainland China after 1998, and suggested that the increase in annual mean maximum temperature obviously slowed down during this time, which may have contributed to delayed rising of annual mean surface air temperatures and the decreased differences of maximum and minimum temperatures, whereas seasonal mean maximum temperatures in summer generally increased. Zheng et al. (2015) and Duan and Xiao (2015) recently reported new characteristics of surface air temperature change in the Qinghai–Tibetan Plateau, showing that, after 1998, the slowdown of climate warming in this area was generally undetectable, and a continual rise in the plateau's surface air temperatures in recent years was prominent.

Overall, higher quality observational data with good spatial and temporal resolutions have been used to study surface air temperature change in mainland China in the past more than half century, and homogenized historical temperature data has begun to be applied since the early part of the new century. Research towards these ends has gradually evolved and resulted in a better understanding of mainland China surface air temperature change, including its spatial differences, seasonal characteristics, diurnal patterns, and possible driving forces and mechanisms.

4. Urbanization effects on temperature trends

It had been a highly debated and unresolved issue regarding the urbanization effect or effect of enhanced urban heat island intensity on surface air temperature trends (Ren et al., 2005c; Ren and Ren, 2011). This issue could not be ignored in the analyses of surface air temperature change and in developing climate change monitoring services. Chinese scientists systematically investigated this problem and obtained a number of new results in recent years (e.g., Ren et al., 2005c, 2008, 2015; Hua et al., 2008; Yang X. C. et al., 2011; Wang and Ge, 2012; He et al., 2013; Wang et al., 2013; Wu and Yang, 2013; Yang Y.-J. et al., 2013; Sun et al., 2017). The IPCC AR5 partly considered the research results concerning mainland China and other regions, and suggested for the first time that the bias from urban warming tended to be more obvious in regions with rapid economic development, but also suggested that it had little influence on the hemispheric and global scales (IPCC, 2013).

Wang et al. (1990) and Zhao et al. (1990) showed that Chinese urbanization had an effect on surface air temperature trends as estimated at northern and eastern urban stations. Zhao et al. (1990) found that annual mean temperature and annual mean minimum temperature rose more noticeably at urban stations compared to rural stations. In particular, annual mean minimum temperature had a more noticeable increase. Concurrently, Qiao and Qin (1990) also highlighted this problem, suggesting that bias from urbanization might have affected the temperature trends at the county-level weather stations in China. Further, Zhao (1991) analyzed annual and seasonal mean temperature trends in mainland China and evaluated the effects of urbanization on temperature changes, suggesting that an obvious increase in annual mean temperatures at the stations from big cities during the previous 39 years appeared, with linear trends of 0.27 to 0.45°C, whereas the temperature trends of the stations from small cities and towns were only 0.04 to 0.12°C. This finding was supported by Portman (1993) who reported a significant difference of temperature trends during 1954–1983 between 21 urban stations and 8 rural stations in North China. These early research efforts were the first to identify the effects of urbanization on the long-term trends of surface air temperature for urban stations across mainland China.

In the mid and late 1990s, studies of urbanization effects on surface air temperature change quieted. An emphasis on the evaluation and correction of systematic bias from urbanization effect in surface air temperature data series was reiterated following the Science and Technology (S&T) Project of the National "Tenth Five-Year-Plan" of China that was approved in 2001 and the subsequent S&T Projects of the National "Eleventh Five-Year Plan", which financed, among others, the systematic examination and evaluation of urbanization effects on observational records of surface air temperature in mainland China (Ren et al., 2005c, 2008, 2015; Ding and Ren, 2008; Ren and Zhou, 2014).

Compared to previous analyses, studies of the last 15 years bear a few of advantages. First, much denser and updated-to-present observations have been applied, with the spatial and type representatives of the temperature data having been substantially improved. Second, the data inhomogeneity problems due to station relocations and other factors in the data series have been partially solved, which allows the use of homogenized historical observation data in the studies of urbanization bias. Third, study objectives have been more explicit and included different types of urban station networks, and in particular, the national reference climate stations and national basic meteorological stations, which have been generally used in climate change research. Fourth, the selection methodology of reference station networks and reference stations has been further developed, including comprehensive methodologies to consider various factors and the incorporation of land surface brightness temperature and visible light data from satellite remote sensing products into the selection criterion. Fifth, metric indicators including urbanization effect and urbanization contribution have been developed, which has significantly facilitated the interpretation of the scientific implications of results.

Research results over the past decade consistently show that large and significant biases from urbanization effects exist in the currently used surface air temperature data series in mainland China. For instance, in a study by using a reference temperature dataset from 143 stations developed based on a comprehensive method for selecting rural stations (Ren Y. Y. et al., 2010; Ren G. Y. et al., 2015), Zhang et al. (2010) confirmed that the effect of urbanization on the country-average annual mean surface air temperature trend of the national reference climate stations and national basic meteorological stations from 1961 to 2004 was at least 0.076°C decade^{-1}. This impact was highly statistically significant, and the contribution of urbanization was greater than 27.3%. Moreover, the urbanization effects in mainland China as a whole were highly significant across all seasons. With an exception of northern Xinjiang, the warming trends resulting from urbanization in different regions of the country were all significant. This was particularly apparent in the Jianghuai region where the urbanization effect reached over 0.086°C decade^{-1} and the urbanization contribution was higher than 55.5%. Recently, Ren and Zhou (2014) analyzed the urbanization effects on the extreme temperature indices using the same reference network data as Zhang et al. (2010), and found that urbanization in mainland China had a significant influence on the long-term trends of annual and seasonal mean minimum temperature ($T_{\min}$), average temperature (T_{avg}), DTR, and other extreme temperature indices from 1961–2008, which are commonly used internationally. In particular, the urbanization effects on the upward trend of $T_{\min}$ and the downward trend of DTR were large and highly significant, with the urbanization factors accounting for at least 32% of the negative trend of annual mean DTR in mainland China. This suggests that urbanization not only significantly changed the mean surface air temperature trends on the sub-continental scale but also led to a significant systematic bias in the time series of the extreme temperature indices.

In general, the observational temperature records of urban and national stations in mainland China have been significantly affected by urbanization since mid 20th century, regardless if the data were homogenized. This basic conclusion was confirmed and supported by many independent studies of the country (Hua et al., 2004; Huang et al., 2004; Zhou et al., 2004; Chen et al., 2005; Chu and Ren, 2005; Liu et al., 2005; Zhang and Ren, 2005; Zhou and Ren, 2005, 2009; Bai et al., 2006; Ren et al., 2007, 2008, 2015; Hua et al., 2008; Tang et al., 2008; Zhao et al., 2009; Li et al., 2010b; Ren and Ren, 2011; Yang X. C. et al., 2011; Yang Y.-J. et al., 2013; Wang and Ge, 2012; He et al., 2013; Li and Huang, 2013; Wang et al., 2013; Wu and Yang, 2013; Ren and Zhou, 2014; Zhang et al., 2014; Bian et al., 2015; Shi et al., 2015; Wang and Yan, 2016; Sun et al., 2017). These investigations varied in study area, study period, the data used, the indices considered, data processing methods, and target stations selected. The major differences that do exist among these studies result from the different methods to determine the reference stations and to establish the reference temperature series. However, overall, all studies agreed that urbanization has had an obvious and in most cases significant effect on land surface air temperature trend estimates in mainland China over the past decades.

The above studies represented an important step toward more accurate monitoring and research of regional climate change. They showed that the systematic bias or urban bias in the surface air temperature data series caused by urbanization on the sub-continental scale is in the same order of magnitude with the overall warming trends estimated by different research groups. These results were contrary to previous high-profile and far-reaching studies by some climatologists including those by Jones et al. (1990, 2008), Peterson (2003), and Parker (2006). Based on these Chinese studies, the IPCC AR5 pointed out for the first time the marked effect of urbanization on regional surface air temperature trends in rapidly developing regions including mainland China. The report indicated that the effects of urbanization were up to 20% of the overall temperature trends in eastern China as a whole, as estimated from the currently used datasets. It should be noted that this conclusion is clearly conservative, considering the Chinese studies mentioned above.

A longstanding problem in regional climate change research could also be explained by the above studies. The rate of increase in the annual mean surface air temperature in mainland China was more rapid than those of the global and the Northern Hemispheric averages since the 1950s, regardless of whether 160, 730, or 2400 station observation data were used, and whether or not homogenized temperature data were applied. Estimates of the temperature trends based on homogenized data of national reference climate stations and national basic meteorological stations are nearly one times larger than those reported for global and the Northern Hemispheric averages. It is clear at present that the significantly higher rate of temperature increase in mainland China mainly results from the effects of urbanization on surface air temperature observations. If the urbanization biases were excluded from the current historical data series, the rate of temperature increase for the country-average annual mean surface air temperature in mainland China is approximately the same as global and Northern Hemispheric averages over the last several decades (Ren et al., 2012; Sun et al., 2016).

Previous studies have indicated that the rising trend of annual mean surface air temperature was approximately 0.25°C decade^{-1} in mainland China over periods beginning from the 1950s (Wang et al., 2004; Ren et al., 2005c; Ren et al., 2012). Many studies have estimated the systematic biases due to urbanization and indicated the contribution rates of at least 25% of urbanization to the annual mean temperature trends, based on datasets from national reference climate stations and national basic meteorological stations (Ren et al., 2008, 2015; Zhang et al., 2010; Yang et al., 2011; Wang and Ge, 2012; He et al., 2013). Recently, based on the data of 2400 observational stations across mainland China, an attribution analysis showed that annual mean surface air temperature change due to urbanization was found to be 1/3 of the overall temperature increase in mainland China (Sun et al., 2016). Considering a conservative urbanization effect of 30% in the overall upward trend, the warming rate of the country-average annual mean surface air temperature would be reduced to about 0.17°C decade^{-1} over the past half a century, which is approximately the same as global average trend estimates given by IPCC AR5 (IPCC, 2013).

5. Conclusive remarks

Studies of land surface air temperature changes in mainland China continue to be vigorously conducted and expanded in many areas. The achievements are inseparable from the efforts of Professor Shaowu Wang and other early-time climatologists. However, there are some major issues that need to be solved in the studies of surface air temperature change in the country (Ding and Ren, 2008; Wang et al., 2009; Ren et al., 2012; Wu et al., 2014; Ding and Wang, 2016). The issues that remain unresolved consist of the following. First, the absence of early-year observational records, particularly in western China, brings considerable uncertainty to the studies of long-term surface air temperature changes over the past century. Second, there are serious inhomogeneity problems in the observational surface air temperature data series in mainland China, which could make analyses of trends less reliable, especially for the analyses based only on the data from a single station or a small number of stations. Third, the historical temperature data from urban stations contain systematic biases caused by the unprecedented urbanization process, which should be evaluated and adjusted accordingly in future. Fourth, studies of extreme temperature change over longer periods, including the first half of 20th century, have been comparatively scarce due to limited high-quality daily temperature data. Fifth, studies regarding the mechanisms of long-term observed surface air temperature changes over mainland China are only beginning, and it is thus necessary to strengthen the research in this area.

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