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ORIGINAL PAPER

The effects of urbanization on temperature trends in different economic periods and geographical environments in northwestern China

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Abstract Using data collected from 22 urban and 65 rural meteorological stations in northwestern China between 1961 and 2009, this paper presents a study concerning the effects of urbanization on air temperature trends. To distinguish among the potential influences that stem from the economic development levels, population scales, and geographic environments of the cities in this region, the 49-year study period was divided into two periods: a period of less economic development, from 1961 to 1978, and a period of greater economic development, from 1979 to 2009. Each of the cities was classified as a megalopolis, large, or medium–small, depending on the population, and each was classified as a plateau, plain, or oasis city, depending on the surrounding geography. The differences in the air temperature trends between cities and the average of their rural counterparts were used to examine the warming effects of urbanization. The results of this study indicate that the magnitude of warming effects due to urbanization depends not only on a city's economic level, but also on the population scale and geographic environment of the city. The urbanization of most cities in northwestern China resulted in considerable negative warming effects during 1961–1978 but evidently positive effects during 1979–2009. The population scale of a city represents a significant factor: a city with a larger population has a stronger warming influence, regardless of whether the effect is negative or positive. Among the three geographic environments of the cities considered, plateaus and plains more significantly enhance warming effects than oases. The urban population trend has a very significant logarithm relationship with the urban temperature effect, but no clear relationships between urban temperature effects and city elevation were detected. The majority of the temperature trends, accounting for more than 60 % of the trends during 1961–2009, can be explained by natural factors, although urbanization has had some obvious effects on temperatures in northwestern China.

1 Introduction

Many studies have concentrated on climate change in recent decades, with more and more of the literature predicting that anthropogenic activities may be the most important force driving global warming. The fourth assessment report of Intergovernmental Panel on Climate Change (IPCC) (Trenberth et al. 2007) stated that between 1906 and 2005, the global surface air temperature increases at an average annual rate of 0.74 °C (0.56–0.92 °C/100 a) which is a higher estimate than that of IPCC's Third Assessment Report, which was 0.6 °C (0.4–0.8 °C/100 a). Research results related to temperature trends in China have appeared in a number of studies in the past 20 years. Wang et al. (1998) observed that the average temperature in China increased by 0.44 °C from 1880 to 1996. Ding et al. (2007) found that the rate of increase in surface temperatures in China climbed to 0.79 °C/century (1905–2001) and was higher, 1.1 °C/50a, in the latter half of that period (1951–2001). Zhou et al. (2004) reported that surface temperature warming trends ranging from –0.112 to 0.494 °C/10 a have been detected in different regions across China. Li et al. (2012) reported that the temperature in

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northwestern China has increased by 0.325–0.360 °C in the last 50 years.

In recent years, considerable evidence has been presented to demonstrate that anthropogenic activities have contributed to urban warming trends. The increasing expansion of built-up areas, the reduction of urban vegetative areas, the abundant emission of greenhouse gases, and some other activities have apparently altered the surface energy radiation balance (Karl et al. 1988; Oke 1988; Kalnay and Cai 2003; De Laat and Maurellis 2006). In addition, the observation of surface temperatures is affected by changes in the nearby thermal environment. Anthropogenic effects on temperature exist over most areas of the continents, even in remote mountain areas. Block et al. (2004) reported that anthropogenic heat emissions raised surface temperatures by 0.15 to 0.5 K in the Ruhr area in Germany. Hua et al. (2008) and He et al. (2006) reported that urban heat island (UHI) effects occurred mainly in regions with rapid industrial and economic development and that the UHI effects of many large cities in China could reach 0.74 K. Hinkel et al. (2003) even detected an average UHI of 3.2 K in the small city of Barrow, Alaska.

However, not all scholars agree with the viewpoint that anthropogenic activities alone drive global warming, and some scientists think that many other uncertain factors may promote changes in temperature (Gong and Wang 2002; Parker 2004; Ding et al. 2007; Maria and Henrique 2008). As some researchers have indicated, most of the climate records used to analyze global temperature changes were derived from large cities, and most instrumental records for these studies are shorter than 100 years. In addition, biases in observation instruments, adjustments to observation times and sites, and the quality of long-term proxy data could all contribute to uncertainty in climate change estimates (Lowry 1977; Gong and Wang 2002; Ren 2008; Ren et al. 2010). Moreover, the spatial and temporal scales of the research data for climate change, the quantity and quality of the climate data, and the analysis methodologies employed are all crucial factors in the analysis of local, regional, hemispheric, and global climate changes (Hansen and Lebedeff 1988; Jones and Briffa 1992; Jones 1994; Jones and Moberg 2003; Mangeri and Nanni 1998). In addition, the selection of different rural meteorological stations to detect the effects of urban areas on temperature trends (i.e., urban heat islands) could result in different values, because different rural stations have different climatic biases, due to various environmental and anthropogenic factors (Oke 1973).

The most anthropogenic impact on temperature is believed to be associated with cities, as some statistical investigations have demonstrated that more than 70 % of global greenhouse gas emissions occurred in cities (OECD 2010). Land use and vegetation have increasingly changed in Chinese cities, especially after the policy of reform and openness was implemented in 1978. These land use and vegetation changes have resulted in obvious UHI effects, not only in large cities but also some medium- to small-sized cities as well (Lin and Yu 2005; Huang et al. 2004). Similarly, UHIs can be observed in some cities in northwestern China that have relatively lower levels of economic development and relatively lower population densities. According to Bai et al. (2005) and Tian et al. (2006), the UHI effects in Xian and Lanzhou ranged from 0.99 to 1.10 °C during the 1990s, but the average UHI in northwestern China was only 0.01 °C (Li et al. 2004).

In northwestern China (hereinafter referred to as NWC), there are many rural stations that are slightly affected by anthropogenic activities because of lower economic levels and smaller populations, unlike those regions in southern and eastern China that are highly developed and crowded. Therefore, NWC could be a significant region for studying and isolating temperature bias from urbanization and anthropogenic activities. In this study, we examine urban effects on temperature changes in NWC.

2 Materials and methods

2.1 Study area and data sources

2.1.1 Description of the study area

In terms of administration, northwestern China consists of five provinces: Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang. It is situated in the center of the Eurasian continent (73.56–111.50°N, 31.58–49.49 °E), with a total area of 3.1×10^6 km^2. The elevation of most of the region is greater than 1,500 m, and the hungriness, desert, mountain, and plateau areas make up 90 % of the total area of NWC. The highest and broadest plateaus in China and the three largest deserts are all situated in NWC; therefore, mountain, plateau, and desert topography exert direct climatic control. The average annual temperature of NWC is approximately 8 °C, and the annual rainfall is less than 400 mm on average, gradually decreasing from east to west. Northwesterly winds prevail annually from the mountain and plateau regions to the plains, and a high-pressure system settles over NWC most days of the year. The NWC region is a typical arid and eco-fragile area because of a shortage of water resources, widespread desertification, and sparse vegetation. The plain, oasis, and other livable areas are less than 10 % of NWC, and the forest coverage is less than 6 %. With approximately one third of the land area of China and 7.2 % of the population, the gross domestic product of NWC is less than 5.6 % of the total gross domestic product of China (China Population Statistics Yearbook 2003). NWC has always been an economically backward region due to its harsh natural climate and fragmented geographic conditions.

2.1.2 Study data

The data used in this study consisted primarily of the mean annual temperatures (Tmean), the mean maximum daily temperatures (Tmax), and the mean minimum daily temperatures (Tmin) measured at 192 meteorological stations in NWC from 1951 to 2009. These data were obtained from the China Meteorological Information Center (CMIC). Average daily temperatures were calculated as the mean values of the temperatures at 02:00, 08:00, 14:00, and 20:00 Beijing time (GMT+8). All the 192 meteorological stations selected for this study had been maintained in accordance with the standards of the National Meteorological Administration of China. The data were treated strictly homogeneously, including extreme inspection, time consistency check, and other checks, before being released. The data used in this study were extracted from the Chinese Ground Climatic Dataset (version 3.0), which is maintained by CMIC. The dataset includes some stations with several years of missing annual data. Based on the principles of data continuity and integrality and a balanced distribution of cities, data measured at 87 stations from 1961 to 2009 were selected for use in this study. To maintain the objectivity of the research results, we did not interpolate time series for those stations that lacked some data; stations were not included in the calculations for periods for which they were missing data. The city population data were extracted from the China Population Statistics Yearbook.

2.2 Study method

2.2.1 The classification of economic levels

Some studies have suggested that the urbanization development process should be classified into different phases by economic levels. To distinguish the effects of urbanization on temperature trends during different economic periods, as other scholars in China suggest, we divided the period of 1961–2009 into two periods, based on China's "economic reform and openness" policy, which was launched in 1978. The economy in NWC gradually developed as a result of this policy and financial support from the state government, and many cities and towns expanded rapidly, with some even becoming large- and mid-scale cities. Therefore, in this division, 1961–1978 was defined as a period of little economic development (before economic reform, BER), and 1979–2009 was defined as a period of greater economic development (after economic reform, AER).

2.2.2 The classification of city scale

Classifying meteorological stations into different types is also a key procedure in urban effect studies. Some researchers have employed "night lights" data derived from satellite telemetry to identify city regions (Gallo and Owen 1999; Hansen et al. 2001). Night lights data may be more objective than estimates based on city population data; however, systematic night lights data are still not available for all areas of China, due to imbalances in economic development, lifestyles, awareness of methods for saving energy, and other factors. Thus, in this study, population data based on the sixth census of China (2003) were employed to distinguish between urban and rural stations. Considering the ratio balance for different city ranks in NWC, the stations were classified into four levels by population: megalopolis city, large city, medium–small city, and rural station. Based on the population information in the China Population Statistics Yearbook 2003, available rural observatories in dataset, and city location distribution balance, we selected 4 megalopolis cities (with populations greater than 1.0×10^6), 7 large cities (with populations of 1.0×10^6–0.5×10^6), and 11 medium–small cities (with populations of 0.2×10^6–0.5×10^6) (as shown in Table 1).

2.2.3 The classification of city geographic conditions

The cities in NWC are located in various geographic environments, i.e., plateaus, oases, river valleys, etc. To analyze urban effects on temperature in different cities, we divided 22 cities into 3 categories: plateau cities, plain cities, and oasis cities. A plain city has a surrounding environment of plains, the natural vegetation is mainly temperate broad-leaved forests, and the climate is mild and humid. A plateau city has an average altitude of more than 1,000 masl, the natural vegetation is mainly alpine meadows, and the climate is cool and dry. An oasis city has a surrounding geographical feature of hungriness, there is a lack of vegetation, and the climate is characterized by extreme drought.

2.2.4 The selection of rural observatories

In this paper, we compared the rural observatory classification criteria provided by Wang et al. to evaluate the rural observatories. Peterson (2003) suggested that an observatory in a town with a population of less than 10^4 people can be considered a rural station and does not require any adjustment for urbanization temperature research. Wang et al. (1990) identified rural observation stations as those with less than 1.47×10^5 inhabitants. Karl et al. (1993) stated that a rural observatory in China with a population of less than 1.6×10^5 is free from the UHI effect. On the basis of these criteria, we identified stations with a population of less than 10^5 as rural observatories in this study. Based on the reasons given above, the selection of rural observatories for this research mainly depended on the following rules:

Table 1 The classifications and properties of the cities

City name	Population (unit, 10^4)	Elevation (unit: m)	The average distances between urban and rural stations		Geographic property	City scale
			horizon (unit: km)	vertical (unit: m)		
Lanzhou	186	1,518	36.43	254.5	Plateau	Megalopolis city
Urumchi	159	935	118.17	318.0	Oasis	
Xi'an	344	398	75.62	316.5	Plain	
Xining	111	2,262	90.23	235.5	Plateau	
Baoji	92	612	108.46	161.0	Plain	Large city
Hanzhong	75	509	107.38	434.0	Plain	
Shihezi	51	443	143.81	19.1	Oasis	
Tianshui	87	1,143	45.71	12.5	Plain	
Yanan	54	1,059	96.82	85.0	Plateau	
Yinchuan	92	1,112	96.91	114.0	Oasis	
Yulin	58	1,058	72.40	39.5	Oasis	
Akesu	43	1,104	178.78	503.3	Oasis	Medium–small city
Ankang	46	291	77.89	298.5	Plain	
Germu	19	2,809	149.00	18.0	Plateau	
Hetian	28	1,375	172.96	23.3	Oasis	
Jiuquan	31	1,478	82.31	253.5	Oasis	
Karamay	25	450	124.35	328.8	Oasis	
Kashi	45	1,289	148.26	688.5	Oasis	
Korla	40	932	144.05	381.5	Oasis	
Qingyang	30	1,421	88.50	201.5	Plateau	
Wuwei	31	1,531	62.88	493.0	Oasis	
Zhangye	32	1,483	70.35	66.5	Oasis	

1. The population of the rural observation station was less than 10^5.
2. The distance between the rural weather station and its associated city station was more than 50 km but no more than 100 km (with the exception of two city–rural stations that were more than 150 km apart and two city–rural stations that were less than 50 km, as shown in Table 1). The relative elevation differential between the city and rural stations was less than 500 m (with the exception of two city–rural elevation differentials that exceeded 500 m, as shown in Table 1).
3. Rural stations were not separated from their urban counterparts by large topographic obstacles, such as mountains, high plateaus, or large canyons.

Based on the above rules, we assume that all of the rural stations were outside the associated cities' UHI plumes and that the corresponding urban stations were located within the same climatic environment as the rural stations, ensuring that the rural and city stations had appropriate comparability. Furthermore, to reduce potential bias from the rural stations, we used two or more rural stations for each city counterpart. This selection process is one way in which this study differed from Karl's study (1988), in which only one rural station was used for comparison with each urban station. Portman (1993) used grouped rural stations for each urban station in comparison research and suggested that more reference stations could reduce the bias from the geographic environment and climatic properties of rural stations. Figure 1 shows the spatial distribution of the cities' weather stations and their rural counterparts in NWC.

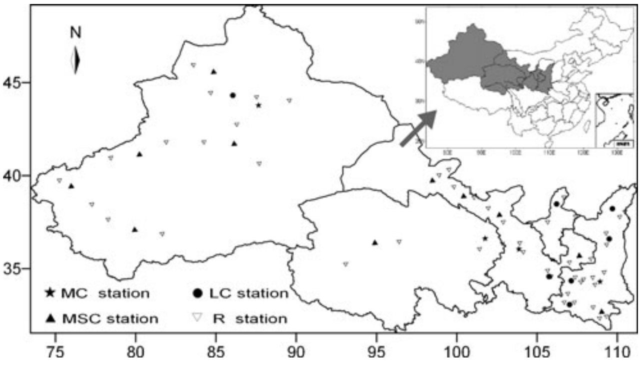

Fig. 1 Spatial distribution map of the urban/rural stations for the urbanization effect study. *MC station*, *LC station*, *MSC station*, and *R station* denote megalopolis city weather stations, large city weather stations, medium to small city weather stations, and rural weather stations, respectively

2.2.5 The calculation method of urban effect

The differences in the temperature trends between the urban and rural stations were ascertained to evaluate the urbanization effect. The urbanization effect on the temperature trends for a single city is calculated using the formula below:

$$\mathrm{Ue}_{i,j} = \mathrm{Tu}_{i,j} - \overline{\mathrm{Tr}_{im,j}} \tag{1}$$

where $\mathrm{Ue}_{i,j}$ denotes the urban effect for city j (j from 1 to 22) during period i (i from 1 to 2, namely, BER and AER), $\mathrm{Tu}_{i,j}$ is the linear trend of the original temperature records for city j during period i, and $\overline{\mathrm{Tr}_{im,j}}$ is the average of the linear trends of the rural observatories for city j during period i (with m ranging from 1 to m, i.e., city j has m rural observatories). The linear trend of temperatures was calculated by the least squares method.

$$\mathrm{Ue}_i = \sum \mathrm{Ue}_{i,j}/22 \tag{2}$$

Ue_i is the average urban effect of all cities in period i.

$$\mathrm{Ue}_{i,\mathrm{cityscale}} = \sum \mathrm{Ue}_{i,j}/p \tag{3}$$

$\mathrm{Ue}_{i,\ \mathrm{city\ scale}}$ is the average urban effect of cities with different populations in period i, city scale takes values of 1, 2, or 3 (namely, a megalopolis city, a large city, or a medium–small city), and p is the number of cities with different populations.

$$\mathrm{Ue}_{i,\mathrm{topography}} = \sum \mathrm{Ue}_{i,j}/q \tag{4}$$

$\mathrm{Ue}_{i,\ \mathrm{topography}}$ is the average urban effect of cities in different geographical conditions in period i, topography takes values of 1, 2, or 3 (namely, a plateau city, a plain city, or an oasis city), and q is the number of cities with different geographic conditions.

$$\mathrm{TD}_{u-r} = T_{\overline{u}} - T_{\overline{r}} \tag{5}$$

TD_{u-r} is the difference between the trend of the average temperature of the cities (22 urban stations) and that of the average temperature of the rural regions (65 rural stations), $T_{\overline{u}}$ is the trend of the average temperature of the 22 urban stations, and $T_{\overline{r}}$ is the trend of the average temperature of the 65 rural stations.

$$C_{\mathrm{ue}_i} = \mathrm{Ue}_i \Big/ \mathrm{Tu}_i \times 100\ \% \tag{6}$$

C_{ue_i} is the urbanization contribution ratio t to the city temperature trend, and Tu_i is the city temperature trend.

3 Results

3.1 The temperature change trend over NWC

3.1.1 The characteristics of the changing trends for Tmean, Tmax, and Tmin

The year-to-year Tmean, Tmax, and Tmin of the rural and urban stations from 1961 to 2009 are depicted in Fig. 2 (denoted a, b, and c, respectively). Based on the temperature trends of NWC, we found that there were three apparent phases of different trends during 1961–2009: a relative steady and low-temperature phase (1961–1983), a fluctuating warming phase (1984–1997), and a steady warming period (1998–2009). Overall, during 1998–2009, most of the stations exhibited strong and steady increasing trends in Tmean, Tmax, and Tmin, except for a few that exhibited inconsistent trends in Tmax (Yulin, Hanzhong, and Baoji). The temperature differences between the urban stations and their rural counterparts in NWC were approximately 1–5 °C for Tmean, Tmax, and Tmin, values that are very close to some of those reported in other UHI research (Lin and Yu 2005, 0.31 °C/10 a in Beijing; Zhou et al. 2004, 0.05 °C/10 a in the southeast; Huang et al. 2004, 0.49 °C/10 a in southern China). In analyzing the three temperature parameters, we found that the Tmax values of the urban stations and their rural counterparts were closer than the Tmin and Tmean values and that Tmin exhibited greater urban–rural differences than Tmax and Tmean, indicating that the upward trend in Tmin could be the most important cause of warming in the cities. The urban–rural temperature difference evolutions of the 22 cities shifted irregularly during the most recent 49 years with respect to Tmean, Tmax, and Tmin, but the urban–rural differences increased gradually over time. For a single city, the urban–rural differences for the various rural stations were very similar, although individual rural stations exhibited irregularly abrupt trends. As some previous studies have suggested, climate changes have apparently local or regional characteristics because geographic conditions could have a considerable impact on local climates, such as in NWC, which is made up of a great plateau, mountains, oases, deserts, and plains. Thus, the observation of such irregular trends in a few cities in NWC is a common phenomenon.

A comparison of Fig. 2a–c indicates that all three temperature parameters for the rural and urban stations exhibited some surprisingly synchronous fluctuating trends, which occurred on cycle of approximately 5–6 years, and a similar scope in variation. The Tmins of the rural and urban stations displayed the fastest warming trends during 1961–2009. There were approximately three types of changes in the temperatures in NWC: a steady upward trend in the plains, a sharp upward trend in the plateaus, and a fluctuating upward trend in oases.

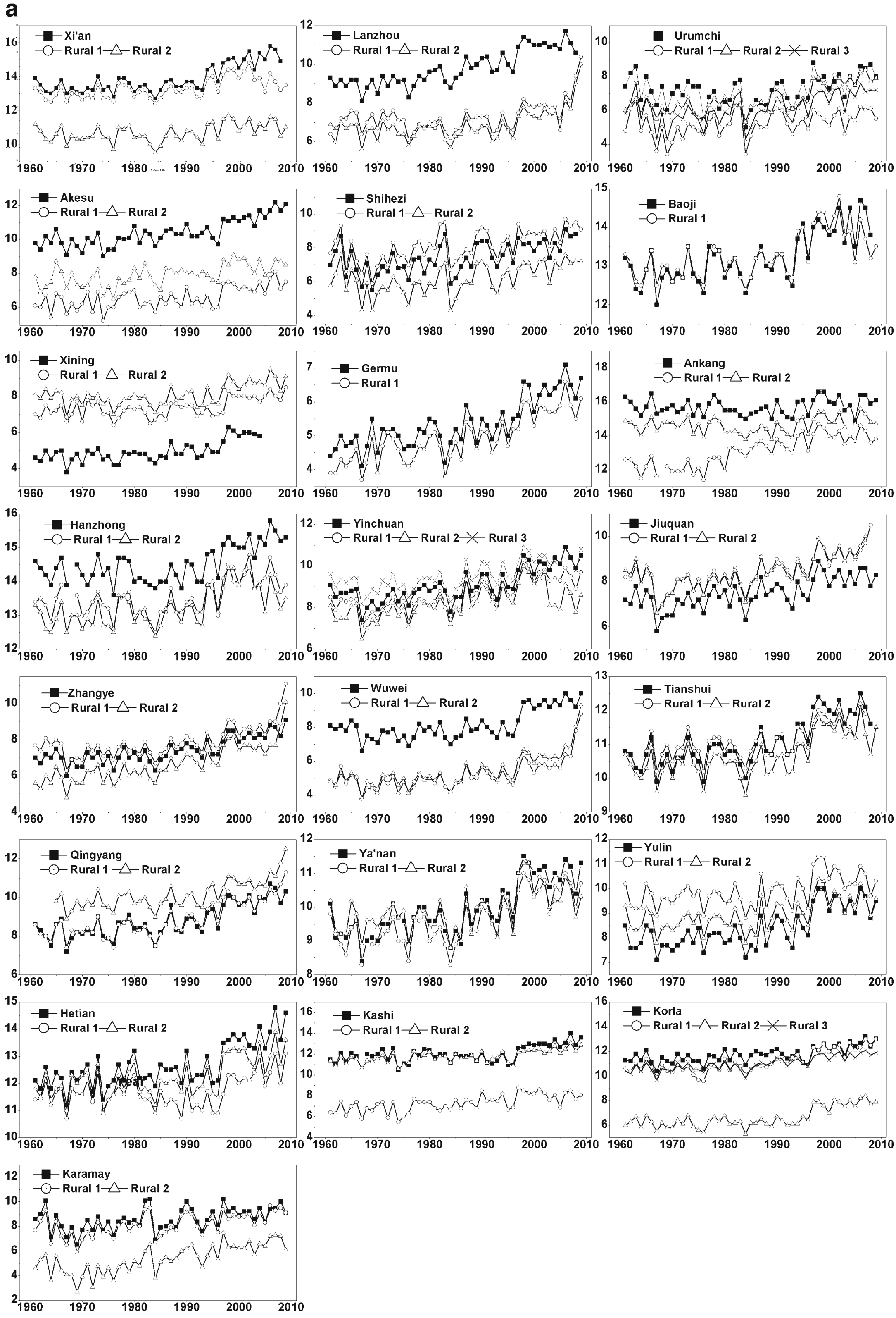

Fig. 2 **a** Time series of the temperatures of the urban stations and their rural counterparts for Tmean (unit: degrees Celsius). The *black lines* represent the temperatures of the city stations, and the *gray lines* represent the temperatures of the rural stations. **b** Time series of the temperatures of the urban stations and their rural counterparts for Tmax (unit: degrees Celsius). The *black lines* represent the temperatures of the city stations, and the *gray lines* represent the temperatures of the rural stations. **c** Time series of the temperatures of the urban stations and their rural counterparts for Tmin (unit: degrees Celsius). The *black lines* represent the temperatures of the city stations, and the *gray lines* represent the temperatures of the rural stations

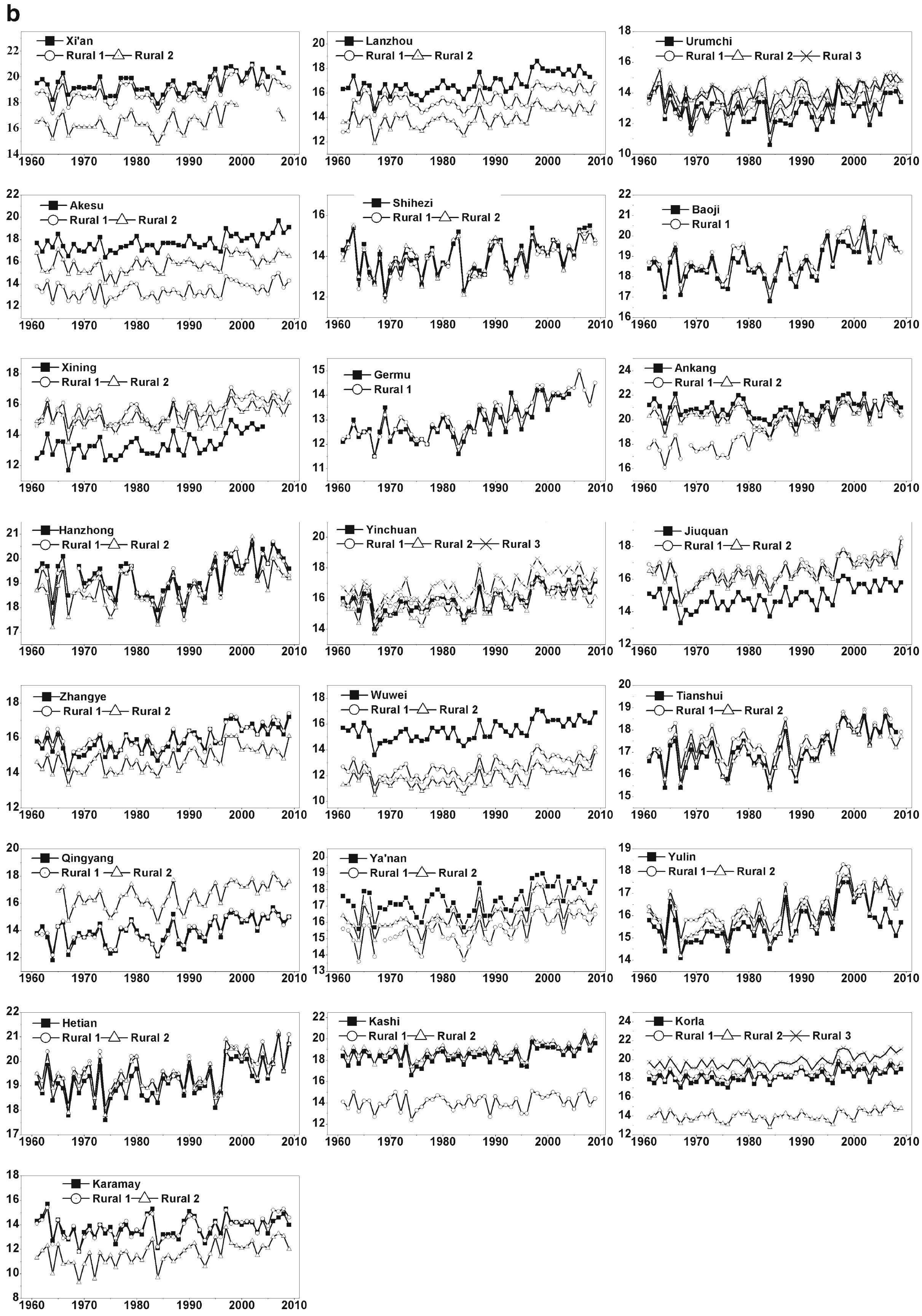

Fig. 2 (continued)

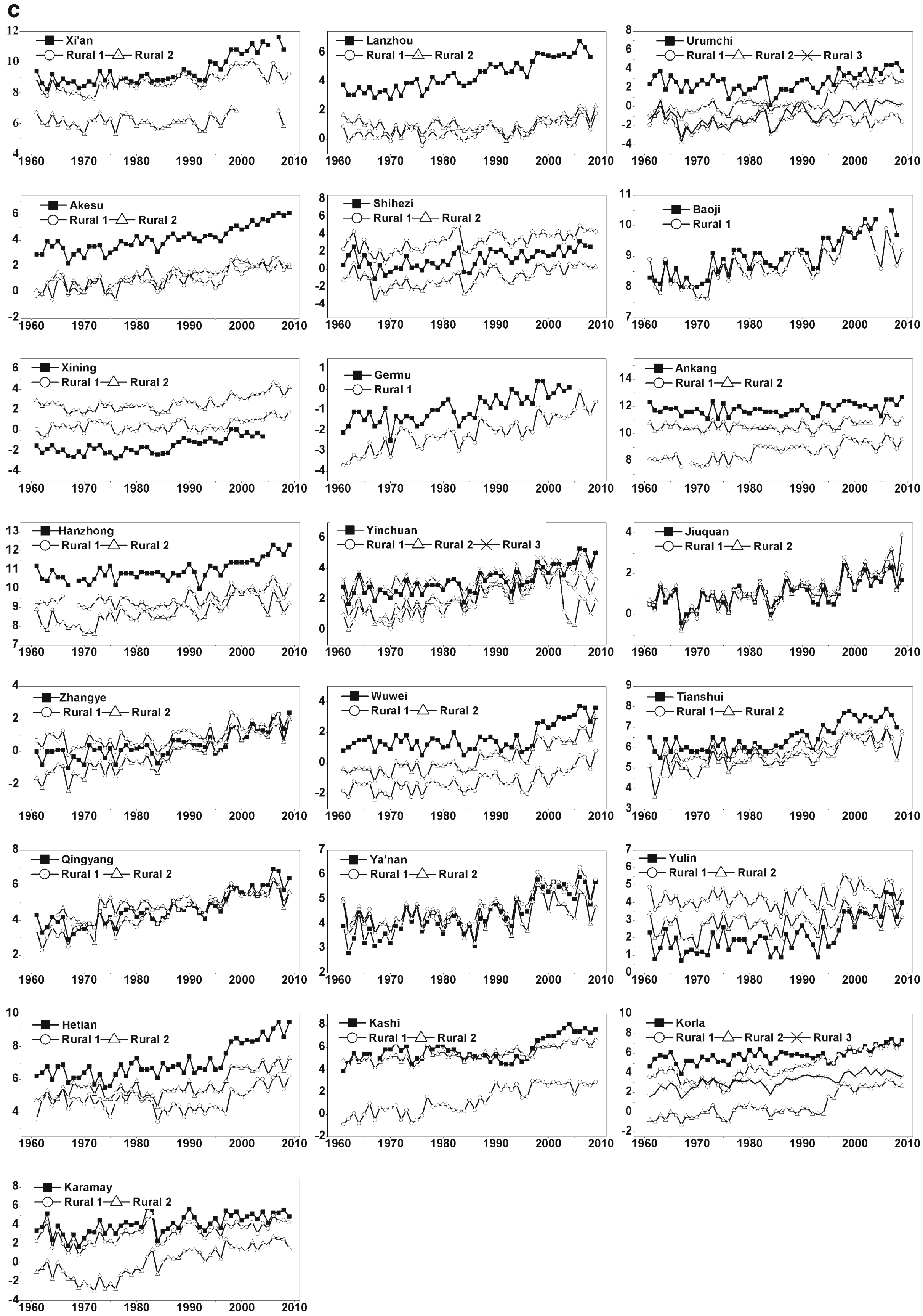

Fig. 2 (continued)

3.1.2 The temperature changing trends in various decades

The mean temperatures have increased overall by 1.70 and 1.63 °C from 1961 to 2009 for the cities (average of 22 urban stations) and rural regions (average of 65 rural stations) (figures omitted), respectively. These warming rates are much greater than some previous research results indicated for China (0.44 °C/100 a, Wang et al. 1998; 0.79 °C/100 a, Ding et al. 2007). As in most studies in China, the 1961–2009 temperature evolution of the northwest can be divided into several phases based on the warming rate. The fourth decade (1991–2000) of this period was the decade that saw the most rapid warming, with an increasing trend of 1.07 °C/10 a (average of 87 stations), accounting for approximately 63 % of the increasing trend of 1961–2009, which is very close to some values reported for other Chinese regions (Zhou et al. 2004; Ding et al. 2007).

There was an unexpectedly lower rate of increase of only 0.23 °C/10 a for the northwestern region during 2001–2009, accounting for just 20 % of the increasing trend of 1991–2000. However, the proportion of the region's population living in urban areas rose from 31.4 to 37.1 % during 2001–2009, which was the second fastest urbanization rate in the past 49 years (see Fig. 3b, urban population ratio variation). A comparison of Fig. 3a (urban temperature trends in different decades) with Fig. 3b reveals that the relationship between surface air temperature trends and urban population trends was not always close during different periods in the northwest, although the temperature trend and population trend are highly correlated with each other overall for 1961–2000 (r=0.92, a=0.01). The temperature trend exhibits a concave-downward parabola shape throughout the entire study period, but the trend in urban population growth was the opposite of the temperature trend. Thus, the UHI effect in the northwest did not always increase the temperature during the period of 1961–2009.

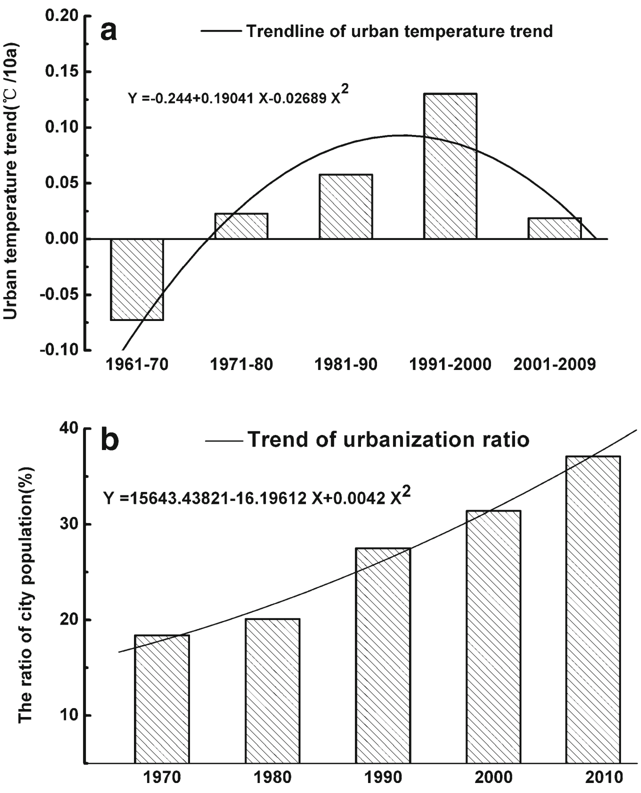

Fig. 3 **a** The urban temperature trends in various decades in NWC. **b** The urban population in various decades in NWC

3.1.3 The trend differences in the urban–rural temperatures

The upward trend differences between the 22 urban and 65 rural stations in NWC were 0.064, –0.07, and 0.005 °C/49 a for the annual mean, maximum, and minimum temperatures, respectively. These urban–rural differences are very similar to those reported in some studies conducted outside China but not similar to results reported in China. Karl et al. (1988) obtained similar results after analyzing the climate data from 1,219 weather stations for which the differences between urban and rural temperature trends were 0.06 °C/84 a for the mean temperature and -0.01 and 0.13 °C/84 a for the maximum and minimum temperatures, respectively. Jones et al. (1990) claimed that the temperature bias due to urbanization was less than one tenth of the global trend. However, the absolute values of the urban–rural differences in this study were far less than those that have been reported for other regions of China. Lin and Yu (2005) suggested that the UHI effect could increase the temperature by 0.31 °C/10 a in Beijing. Zhou et al. (2004) reported that urbanization had increased urban temperatures by 0.05 °C/10 a in southeastern China since 1980. Huang et al. (2004) suggested that the UHI effect raised the urban temperature by 0.49 °C/10 a in southern China.

3.2 The effects of urbanization on temperature in the BER and AER periods

There are two apparent types of urban effects from 1961 to 2009: significant positive effects for warming temperatures during the AER period (1979–2009) and slightly negative effects during the BER period (1961–1978). During the BER period, the urban stations exhibited the strongest negative effect on Tmax, which was −0.11 °C/10 a, but far less negative effects on Tmean and Tmin, which were −0.002 and −0.01 °C/10 a, respectively. During the AER period, however, the urban effects on all three meteorological parameters exhibited stronger positive effects of 0.17, 0.06, and 0.02 °C/10 a for Tmin, Tmean and Tmax, respectively.

Figure 4 shows that the urbanization level or the economic development level plays a crucial role in increasing the surface air temperature, based on a comparison of the

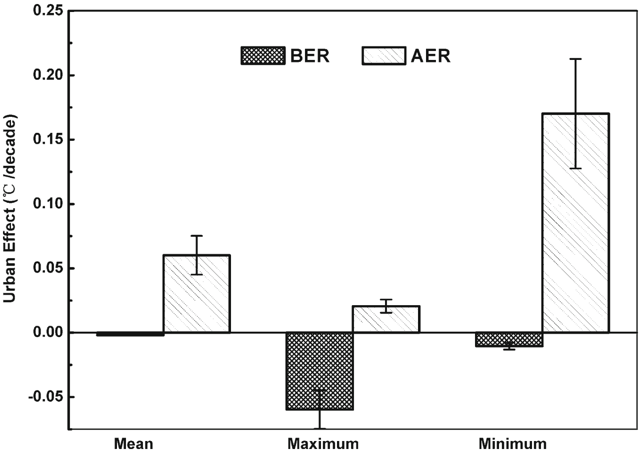

Fig. 4 Average effects of urbanization on Tmean, Tmax, and Tmin during the BER and AER periods

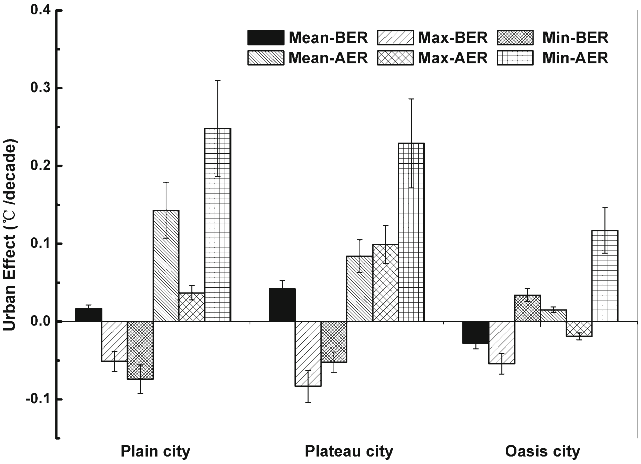

Fig. 5 Effects of urbanization in various geographic environments during the BER and AER periods

temperature variations between the BER and AER periods. First, at the lower urbanization and economic development level (BER), the effects of urbanization on the temperature trends were insignificant and potentially negative. Second, positive effects appeared and were enhanced after the cities developed gradually to a certain economic level. Among the temperature parameters, Tmin was the most affected by the progression of urbanization, followed by Tmax and the average temperature. These conclusions are in agreement with analogous research in the literature (Karl et al. 1988; Portman 1993; Zhou et al. 2004; Fang et al. 2007). Some researchers have argued that the minimum temperature increases faster in urban areas because of gradual increases in greenhouse gas concentrations, which prevent massive longwave radiation from land to sky at night (Oke 1988). However, the redundant aerosol concentration in city atmospheres could prevent Tmax from increasing rapidly, and high-pressure systems could be another factor that reduces the upward trend in Tmax (Ren 2008; Li et al. 2000; Tian et al. 2005).

3.3 The urban effects in different geographic environments

Figure 5 indicates that the environments around cities could have some unusual effects on temperature trends due to the composite nature of their anthropogenic and natural trends with economic development. For Tmax during the BER period, the urban effects on all the plateau, oasis, and plain territories were remarkably negative; however, the effects on Tmax became positive during the AER period, except in the oasis areas. For Tmin, the urban effects of all the geographical regions were congruously positive during the AER period but negative, except for oasis cities, during the BER period. Finally, the urban effects on Tmean generally alternated from lower to higher and from negative to positive during the shift from BER to AER.

Among the geographic environments, plateaus and plains significantly strengthened the urban effects in increasing temperatures, making both positive and negative urbanization effects much stronger than that of the oasis environments. During the AER period, the urbanization effects mainly played positive roles: the urban effects on the minimum temperatures in the plains and plateaus were as high as 0.25 and 0.23 °C/10 a, respectively, approximately twice that in the oases. The urban effects on the mean temperatures in the plains and plateaus were 0.14 and 0.08 °C/10 a, respectively, which were much greater than those in the oases. However, there are inconsistent trends during the BER period: first, the effect on Tmin in oases was positive, in contrast to that in the plateaus and plains; second, the effect on Tmean in the oases was negative, in contrast to that in the plateaus and plains. Finally, the urban effects in the oases were much smaller than in the plateaus and plains, regardless of whether positive or negative effects were involved.

An interesting phenomenon found in this study is the significantly negative effect of urbanization on the temperature trends in all three geographic regions, which has rarely been reported in previous Chinese studies (Su and Hu 1987; Zhou et al. 2004). However, this effect has been documented frequently in some countries and regions outside of China (Oke 1973; Karl et al. 1988; Jones and Moberg 2003), with the magnitude of the effect reported to be even greater in some other studies than in ours. With respect to the negative effect, some studies conducted in China have suggested that it could only occur in some oasis cities due to cool island effects (Su and Hu 1987; Yang et al. 1992; Luo et al. 2004; Pan and Liu 2008).

3.4 The urban effects of different city scales

The population scale of a city, or the city scale, was also found to have a significant impact on urban surface temperatures

(Fig. 6). In general, the greatest effects on the temperature trend, whether negative or positive, always occurred in megalopolis cities, moderate effects occurred in large cities, and the smallest effects occurred in medium–small cities. Megalopolis cities had the greatest positive effect, 0.43 °C/10 a (Tmin in AER), which was approximately 1.7 times that in large cities (Tmin in AER) and 20 times that in medium–small cities (Tmin in AER). Likewise, megalopolises had the greatest negative effect, −0.21 °C/10 a (Tmax in BER), which was four times that of medium–small cities (Tmax) during the same period. For Tmean, Tmax, and Tmin, in both the BER and AER, the megalopolis cities always exhibited the strongest influence on temperatures (see the absolute values of the effects in Fig. 6).

The effects of various city scales on warming also indicate that the negative urban effects that occurred during the BER could turn into positive aspects during the AER period (except for Tmean and Tmax in oasis cities), and the effects of urbanization in the AER period were considerably greater than during the BER period. These results are consistent with those reported in Sections 3.2 and 3.3 and thus offer additional strong evidence that urbanization and economic development has important impacts on temperature variation.

3.5 The roles of population and elevation in the urban temperature effect

Population is an important index of the extent of urban development. It is one indicator of the city scale and is an indicator of the total amount of energy and resource consumption. To analyze the role of population in the effect of urbanization on temperature, we constructed relational models between the city population change (between 1978 and 2009) and the urban temperature effect during AER because urbanization in northwest China began after 1978. Figure 7 shows the relational model of the population change and the urban temperature effect during 1979–2009. The model, which follows a logarithmic curve with correlation coefficients of 0.71–0.75, is significant at the 0.01 level. When the population increases reaches 2.2×10^5, the urban temperature effect is always a positive value with increasing population; however, the urban temperature effects are not consistent when the population increase is less than 2.2×10^5. Negative urban effects were detected for only three cities, Jiuquan, Karamay, and Korla, during 1979–2009, and all three of these are medium–small cities and oasis cities. Thus, the urban cool island effect is enhanced in oasis regions, with the development of cities in these regions possibly reducing temperature uptrends.

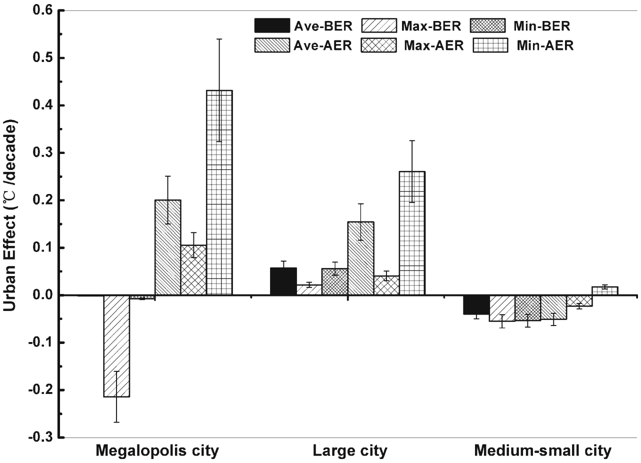

Fig. 6 Effects of urbanization at various urban scales during the BER and AER periods

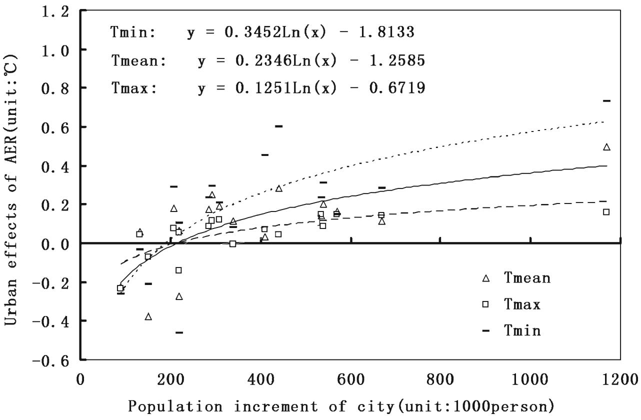

Fig. 7 The logarithm relation of city population increase to urban temperature effect during AER. The *solid line* is the trend line for Tmean, the *dotted line* is the trend line for Tmin, and the *dashed line* is the trend line for Tmax

No clear relationships were detected between the urban temperature effects during 1979–2009 and city elevation, according to the relational models shown in Fig. 8. The linear relationships of urban temperature effects and elevation indicate that the mean temperature and minimum temperature decrease with increasing city elevation, but the maximum

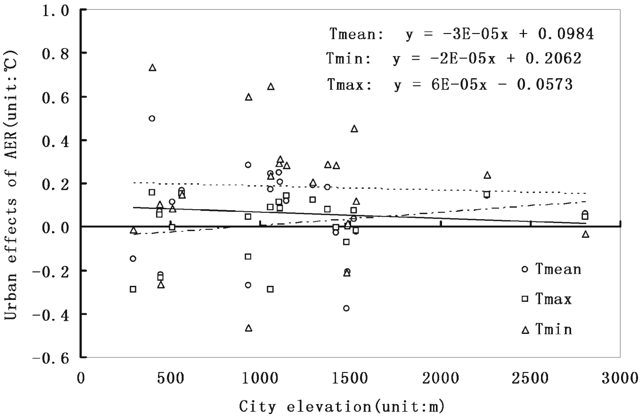

Fig. 8 The relation between city elevation and urban temperature effects during AER. The *solid line* is the trend line for Tmean, the *dotted line* is the trend line for Tmin, and the *dashed line* is the trend line for Tmax

temperature displays the opposite trend. However, none of the linear relationships between urban temperature effects and elevation were found to be statistically significant.

3.6 The contribution rate of the urban effect

The city scale and city geographic conditions in NWC indicate that there are complicated urban effects on city surface temperature records (Table 2). With respect to the city scale, megalopolis and large cities mainly displayed much stronger effects in terms of increasing temperatures, with their contributions to the urban effect accounting for approximately 20–40 % of the cities' uptrends (except for Tmax in megalopolis cities). In contrast, medium–small cities had a weak negative urban effect, with a contribution of approximately −10 %. With respect to geographic conditions, plain and plateau cities had an approximately 10–30 % positive contribution to temperature increases (except for Tmax in plain cities), whereas oasis cities had an approximately −3 to 6 % contribution.

4 Discussion

4.1 Urban effects for various economic levels

We found that the urban effect on temperature depends heavily on the level of economic development of an urban area (i.e., the scale of anthropogenic activities), based on a comparison of their effects before and after the Chinese "reform and openness" project. In this paper, the urbanization effects on temperature during the BER were generally negative for the average, maximum, and minimum temperatures, but the situation was dramatically reversed during the AER. Most previous studies of the urbanization effect on temperatures in China have shown that urban development increases the urban heat island index and that city temperatures always rise faster than rural temperatures (Zhou et al. 2004; Hua et al. 2008). However, Portman (1993) presented results similar to ours, taking into consideration a few Chinese cities where urbanization could have negatively affected surface temperatures. Such large-scale negative effects during the BER (namely, the simultaneous negative average effects for 22 cities for the average, maximum, and minimum temperatures during 1961–1978) have not commonly been reported for NWC, even though the urban effects during the BER were unremarkable, with absolute values rarely exceeding 0.05 °C/10 a. However, the urban effects on Tmean and Tmin increased to 0.06 and 0.17 °C/10 a, respectively, during the AER, accounting for 11.6 and 29.0 % of the uptrends from 1979 to 2009 in the mean and minimum original temperature records, respectively.

Despite these observations, the urbanization effects on temperatures detected in this study were less than those detected in most previous studies with respect to the UHI effect. Jones et al. (2008) suggested that temperature trends may become insignificant over larger regions. Peterson (2003) and Ding et al. (2007) particularly emphasized that the determination of whether a meteorological station was "urban" or "rural" was another crucial factor that could interfere with drawing clear research conclusions. Thus, the large amount of data and large number of cities used in this study, the lower economic levels and lower population levels of some of the cities, and the windy and arid climate in the northwest could together have resulted in diminished urban effects.

4.2 Urban effects for various geographic environments

The geographical conditions of the areas surrounding the cities also played an important role in enhancing or weakening the urban effect. In this paper, plain and plateau cities were found to have stronger warming effects than oasis cities. The ground surface conditions (e.g., ground structure, vegetation area, surface thermal capacity) around plain and plateau cities are essentially consistent with those of the urban areas, whereas the surface and atmospheric conditions around oasis cities are much different than those of urban centers. Oasis cities rarely accumulate greenhouse gas concentrations at levels as high as in plain and plateau cities. Furthermore, because oases more easily exchange thermal amounts with the outside environment due to the windy climate in rural areas in NWC, the urban effects of the oasis cities in this study were relatively weaker, and the effects on the maximum temperature were always negative. Overall, the urban effects of the plateaus, plains, and oases were less than 0.08 °C/10 a (absolute values) during the BER, but rose to 0.25 °C/10 a during the AER.

4.3 The urban effects for various city scales

The urban scale plays an important role in temperature increases, as noted by many scholars. In this study, megalopolis

Table 2 The contribution rate of the urban effect during 1961–2009 for different types of cities (unit: percent)

	Tmean	Tmax	Tmin		Tmean	Tmax	Tmin
Megalopolis city	30.31	−4.13	44.42	Plain city	12.49	−32.62	23.04
Large city	23.59	0.50	24.74	Plateau city	24.72	8.81	35.72
Medium–small city	−12.04	−13.08	−11.76	Oasis city	−2.70	−5.93	−4.91

and large cities had much stronger warming effects than medium–small cities. The megalopolis cities displayed both the strongest negative effects (during the BER) and the strongest positive effects (during the AER) on temperature, i.e., less than −0.2 °C/10 a and greater than 0.4 °C/10 a, respectively.

The urbanization effects on temperature trends were intense for some individual cities. Negative urban effect of −0.31 °C/10 a were detected for Urumchi (a megalopolis and oasis city), −0.48 °C/10 a for Lanzhou (a megalopolis and plateau city), and −0.66 °C/10 a for Germu (a medium–small and plateau city) for the mean, maximum, and minimum temperatures, respectively. The greatest positive effects for individual cities were 0.47 °C/10 a for Xi'an (a megalopolis and plain city), 0.19 °C/10 a for Germu, and 0.72 °C/10 a for Xi'an, for the mean, maximum, and minimum temperatures, respectively.

4.4 The reasons for the negative effects and positive effects

The following factors may explain why cities displayed such significantly and widely negative effects on the temperature records during the BER and strong positive effects during the AER. The first factor is the large-scale and long-term population shifts between the cities and the countryside. The first population shift was from cities (especially from megalopolis and large cities) to villages, occurring from the early 1960s to the late 1970s due to the well-known movement known as "go to the mountainous areas and the countryside." The second movement was from villages to cities, occurring after 1978 because of the reform and openness policy. Massive population immigration and emigration significantly changed the thermal environment of the rural areas due to the gross energy consumption shift, consequently generating a bias in the temperature records. The second factor resulting in the negative effect is the level of economic development. The negative urban effects occurred almost exclusively during the period of lower urban economic development (1961–1978), when an agriculture-dominated developmental pattern was the most important economic feature. Widespread soil reclamation and water conservancy projects were conducted, and many large-sized steelmaking companies and factories were established in the countryside, including the remote mountainous regions, before 1978, accompanied by a continual weakening of the economic conditions near cities. However, this economic development abruptly changed into an industry-dominated pattern after 1978, when a large number of factories and companies opened near large- and moderate-sized cities. The third factor was the tremendous transformation of the city surface structure due to the population levels in megalopolis and large cities. The total population of cities in China before 1978 was far less than that of the rural areas, and the annual increase in the populations of the cities before 1978 was negligible compared with that after 2000. However, urban built-up areas and urban populations quickly increased after 1978 because many farmers moved to the cities and became urban inhabitants. By 2009, the built-up areas and populations reached 3.7 and 6 times, respectively, than their 1978 levels. All these anthropogenic actions, including population moves, economic form shifts, city surface structures, and population growth, could have resulted in unexpectedly negative urban effects during the BER and stronger positive effects during the AER.

5 Conclusions

All of the meteorological station data available in NWC were applied to analyze the urban and rural temperature trends during 1961–2009 and to determine the effects of urbanization on temperature trends. The temperature differences between city stations and their rural counterparts were used to assess the effects of urbanization on temperatures. The mean temperature of northwest China increased by 1.70 and 1.63 °C overall from 1961 to 2009 for cities and rural regions, respectively. These warming rates are much greater than those that have been reported in some previous studies in China. However, the average urban–rural temperature difference, 0.07 °C/49 a, is markedly less than previously documented in China.

Urban temperature effects were found in this study to depend mainly on the economic development level of a city, the geographic environment around the city, and the city scale. The economic development level plays a crucial role in increasing the urban surface air temperature in northwest China. The effects of urbanization on the temperature trends during the period of less economic development (1961–1978) were insignificant and were negative overall. However, the urban effect on temperature during the period of greater economic development was positive and was considerable. The minimum temperature was the most affected by economic development, followed by the mean temperature and the maximum temperature. The geographical environments surrounding cities were also found to play a role in urban temperatures: plateaus and plains increased the urban effect on the minimum temperature approximately twice as much as did oases during 1979–2009. The effect of city scale was different from those of the economic development and geographic environment factors. Megalopolis cities and large cities all enhanced the urban effects during 1979–2009; however, medium–small cities slightly reduced urban effects during the study period of 1961–2009.

The population growth of cities was found to have a very significant logarithm relationship to the urban temperature effect. However, there were no clear relationships between urban temperature effects and city elevation.

Urbanization in northwest China has had some effects on the cities' temperature records. For some cities, the positive contribution accounted for approximately 10–40 % of the urban temperature uptrend during 1961–2009, but there was a negative contribution of approximately 3–10 % for other cities. However, the remaining 60–90 % of the urban temperature uptrend may be explained by non-urbanization factors. As Parker (2004) suggested, “Large-scale warming is not urban.”

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