Theor Appl Climatol (2010) 99:469–478
DOI 10.1007/s00704-009-0155-4

ORIGINAL PAPER

# Assessment of surface air warming in northeast China, with emphasis on the impacts of urbanization

**Qingxiang Li · Wei Li · Peng Si · Gao Xiaorong · Wenjie Dong · Phil Jones · Jiayou Huang · Lijuan Cao**

Received: 21 December 2008 / Accepted: 15 June 2009 / Published online: 4 July 2009


**Abstract** Based on homogenized land surface air temperature (SAT) data (derived from China Homogenized Historical Temperature (CHHT) 1.0), the warming trends over Northeast China are detected in this paper, and the impacts of urban heat islands (UHIs) evaluated. Results show that this region is undergoing rapid warming: the trends of annual mean minimum temperature (MMIT), mean temperature (MT), and mean maximum temperature (MMAT) are 0.40 C decade$^{-1}$, 0.32 C decade$^{-1}$, and 0.23 C decade$^{-1}$, respectively. Regional average temperature series built with these networks including and excluding "typical urban stations" are compared for the periods of 1954–2005. Although impacts of UHIs on the absolute annual and seasonal temperature are identified, UHI contributions to the long-term trends are less than 10% of the regional total warming during the period. The large warming trend during the period is due to a regime shift in around 1988, which accounted for about 51% of the regional warming.

Q. Li (✉) · P. Si · G. Xiaorong · L. Cao
China Meteorological Administration,
46 Zhongguancun South Avenue, Haidian District,
Beijing 100081, China
e-mail: liqx@cma.gov.cn

W. Li
National Meteorological Center,
China Meteorological Administration,
Beijing 100081, China

P. Si
Tianjing Municipal Meteorological Information Center,
Tianjing 300074, China

G. Xiaorong
Institute of Atmospheric Sciences, Lanzhou University,
Lanzhou 730000, China

W. Dong
State Key Laboratory of Earth Surface Process
and Resource Ecology,
Beijing Normal University,
Beijing 100875, China

P. Jones
Climate Research Unit, School of Environmental Sciences,
University of East Anglia,
Norwich NR4 7TJ, UK

J. Huang
Institute of Physics, Peking University,
Beijing 100871, China

## 1 Introduction

Large-scale warming and its impacts on the environment attract more and more attention and interest because surface air temperatures on global or hemispheric scales have increased continuously during recent decades (Jones et al 1986a, b; Hansen and Lebedeff 1987; Vinnikov et al. 1990). According to Trenberth et al. (2007), the global surface air temperature increased about 0.74±0.18 C during the last 100 years, and human modification of the atmospheric composition has made the most crucial contribution to this warming in recent decades. Urbanization and land use changes have also been important human activities during the second half of the twentieth century. Because of global urbanization and changes in land utilization, due to agriculture, herding, industry development, deforestation, desertification, and so on, which could change the land surface physical processes and surface heat flux, there could have been substantial impacts on regional and global climate. Northeast China saw the most significant warming trends in China during last the 50 years (Tu 1984; Wang et al. 1998; Zhai et al. 2004; Li et al. 2004, 2006), but there has been little agreement on the estimated urban and land use contribution to the warming trends (Zhang et al. 2003; He et al. 2007; Ren et al. 2008). In North China, land use changes have been important: firstly, the process of urbanization is accelerating and the population has increased; on the other hand, desertification of north China has accelerated according to remote sensing desert monitoring data in 1975, 1987, and 2000: during 1950–1975, the desert land area was 1,560 km$^2$, while it reached 2,100 km$^2$ in 1976–1988 and 3,600 km$^2$ in 1988–2000 (Wang et al. 2004). Accordingly, investigation of the urbanization and land-use-change effects on the regional climate is both more and more urgent and important.

In China, regional and national temperatures have been monitored by the reference climate stations (RCS, 24 observations (hourly) a day) and basic weather stations (BWS, four observations (02:00, 08:00, 14:00, and 20:00 Beijing time) a day). Some studies have used a dataset of 160 of these stations, quality controlled and maintained by the National Climate Center (NCC), while other studies have used about 300, 500, or even 700 stations from the National Meteorological Information Center (NMIC). Unfortunately, neither set of station series has been tested for homogeneity until recent years: the first homogenized temperature dataset (CHHT 1.0) including all the national stations (NS, including both the RCS and BWS, 731 stations in total) was developed by Li et al. (2004), and Feng et al. (2004) built another dataset including seven quality-controlled climate variables. The CHHT 1.0 dataset was released by the China Meteorological Administration (CMA) in December 2006, and this dataset is widely used in climate change detection in China (Zhou et al. 2004; Zhai et al. 2004; Jones et al. 2008; Ma et al. 2008; Yan et al. 2009), improving the accuracy of regional and local climate trend detection greatly, though it shows no significant differences in the all-China temperature change trend relative to earlier datasets. In recent years, data from ordinary weather stations (OWS) were introduced into studies to detect the regional warming trends (Ren et al. 2007; Ren et al. 2008; Yan et al. 2009), and Ren et al. (2008) argued that most NSs in China were contaminated by urban heat island (UHI) effects.

With economic development in China during the recent 50 years, especially in the recent 30 years since China's Open and Reform Policy started at the end of the 1970s, more and more people live in cities, the evapotranspiration of the land surface land has changed, and some long-wave radiation is blocked by the high buildings. Thus, the local surface air temperature (SAT) increases compared to that of the surrounding rural/suburban sites (Zhou and Su 1994). Karl et al. (1988) analyzed the urbanization effect on US SAT based on the US Historical Climate Network (USHCN) temperature dataset and found that urbanization made the SAT of the USA increase by about 0.06 C in the twentieth century. Jones et al. (1990, 2008) studied station data of western parts of the former Soviet Union, eastern Australia, and eastern China, and showed that the contribution of urbanization to warming is limited. Hansen and Lebedeff (1987) found that the global mean air temperature rise was reduced by 0.1 C after removing the observed data of the cities from the air temperature time series, whose populations are more than 100,000. Houghton et al. (2001) pointed out that the impact of UHI on the global surface mean air temperature changes was less than 0.05 C. Parker (2004, 2006) demonstrated that large-scale warming is not urban by showing that, globally, temperatures over land have risen as much on windy nights as on calm nights. Peterson (2003) analyzed American data and showed that there was no impact of UHI on trends in the mean air temperature in either urban or rural sites. Li et al. (2004) analyzed normalized annual SAT over mainland China from 1954 to 2001, and the rotated empirical orthogonal expansion (REOF) approach was used to divide Mainland China into five subregions. After comparing the annual temperature anomaly series of urban sites with those from non-urban locations, they found that UHI made the mean air temperature of China increased no more than 0.06 C during the last 48 years. On the other hand, some studies have shown that the impact of UHIs on regional and local air temperature trends is much greater (Ren et al. 2007; Yan et al. 2009).

Land use changes are much more extensive than UHIs, and include urbanization, desertification, and development of agriculture, forestry, and animal husbandry. Gallo et al. (1996) found that land use and land cover change had major impacts on the diurnal air temperature range (DTR), which was least at urban sites. Later, Gallo et al. (1999) used the environmental protection meteorological satellite OSL data to study the impact of land use and land cover changes on air temperature trends for the USHCN, and the result showed that every land use and cover change should have some impact on the trend of temperature. Recently, Zhou et al. (2004) used surface station data over southern China and NCEP/DOE AMIP-II Reanalysis (R-2) and analyzed trend differences of the air temperature, with the result indicating that the impact of urbanization on South China temperature was about 0.05 C decade$^{-1}$. Later, Li (2006) analyzed the UHI effect on the regional temperature change during a similar period (1979–2004) with the homogenized dataset with the same classification of the stations and methods used in Li et al. (2004), and found similar results with UHI effects of about 0.030–0.049 C decade$^{-1}$, which shows that UHI effects were extracted properly by Li et al. (2004). South China has undergone the most rapid urbanization in China during the past three decades, and its land-use change is mostly towards

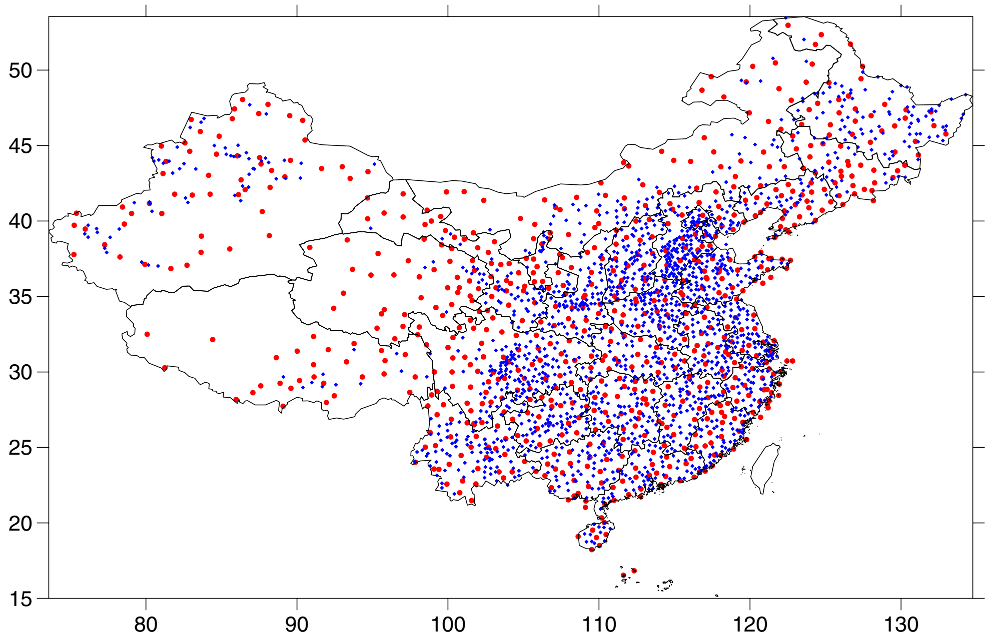


**Fig. 1** The distribution of NS (*red*) and OWS (*blue*) in Mainland China

urbanization (see the People daily article at http://english.peopledaily.com.cn/200111/27/eng20011127/85410.shtml and the State Family Planning Commission of China web site at www.sfpc.gov.cn/EN/enews20030320-1.htm).

One of the goals of this paper is to investigate whether or not the NSs network, i.e., the CHHT 1.0 dataset (Li et al. 2009), is of sufficient station density to represent regional climate changes. Additionally, new proof is provided to confirm the earlier conclusions that UHI should not be the important contribution of regional warming over northeastern China. In this paper, we first present a brief introduction to China's weather observation network and assess the reliability of the CHHT 1.0 dataset for climate analysis. Then, we show in section 3 the annual and seasonal temperature trends over the last 50 years. In section 4, the UHI effect is evaluated based on CHHT 1.0, and in section 5, some discussions are put forward to support the results in the previous sections, and the main conclusions are drawn.

## 2 Observations network and assessment of CHHT 1.0

### 2.1 Brief review of climate/weather observations network in China

Since the 1950s, the surface climate/weather observation network has been classified into three levels: RCS (about 150 stations), BWS (about 550 station), and OWS (about 1,750 stations). All of the data from these stations are stored and processed in the National Meteorological Information Center (NMIC) of CMA. For the first two kinds of station, the average values of four observations at

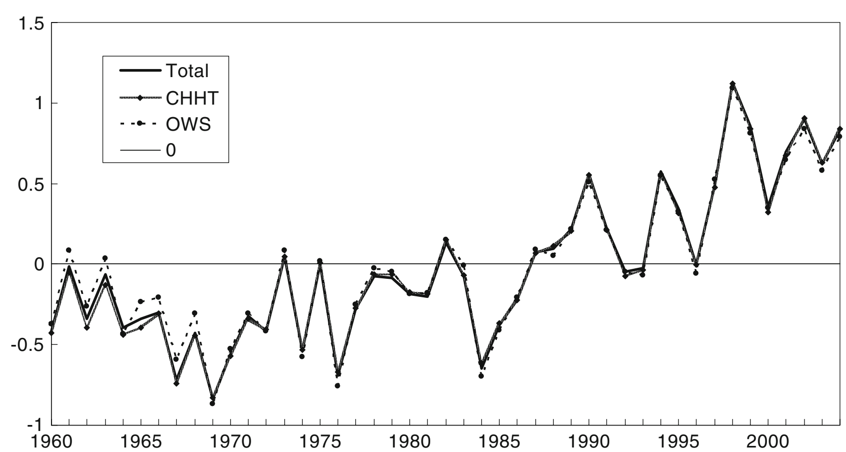


**Fig. 2** Annual MT anomalies for the three networks in China

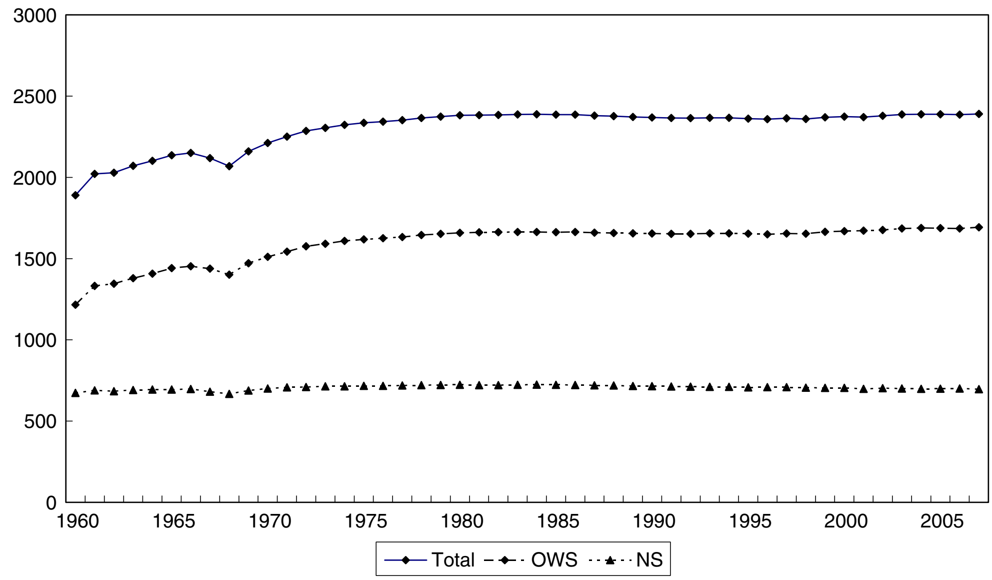


**Fig. 3** Changes in station numbers for the three networks in NE China

0200, 0800, 1400, and 2000 Beijing Time (BT, which is 8 h earlier than UTC) are generally used as the daily mean temperature, and the monthly mean temperature is calculated based on the daily mean temperature. Taken together, these two kinds of stations are called NS. The OWSs do not take measurements at night (02:00 BT), so daily mean temperatures are calculated by the following weighted average: $T$=((Tmin+T8)/2+T8+T14+T20)/4 (Tmin is daily minimum temperature, and Tx is the observation at "X" o'clock BT), but unfortunately, the data for OWS have not yet been strictly quality controlled (QC) and homogenized. The day for maximum and minimum temperature is the 24-h day ($i$) from 20:00 ($i-1$) to 20:00 ($i$).

## 2.2 Assessment of CHHT 1.0

The CHHT Dataset (1951–2004), version 1.0, consists of monthly and daily surface observations from all NSs in

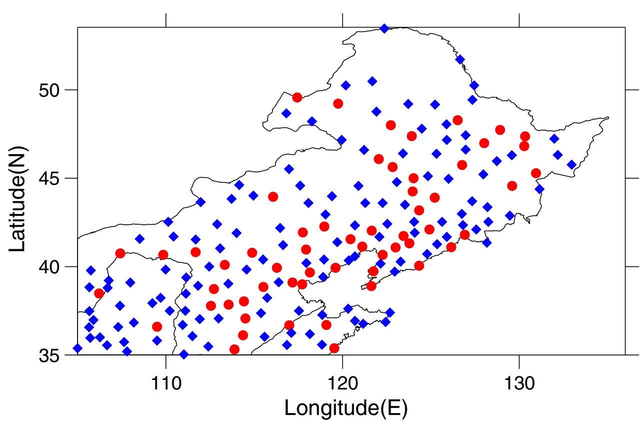


**Fig. 4** Distribution of stations from CHHT 1.0 in Northeast China (*red*—typical urban stations, *blue*—non-typical urban stations)

Mainland China. CHHT 1.0 includes mean, maximum, and minimum temperature data; assessments of data quality; and gridded versions of the three temperature variables (Li et al. 2009).

In China, most of the OWSs were set up in the late 1950s, so we chose 1960–2004 for some comparisons with CHHT 1.0. Figure 1 maps the stations in China for all three networks (NSs, OWSs, and total (NS+OWS)). In total, 671 NSs and about 1,736 OWSs stations were available for the most recent year in the networks.

For developing the gridded version of CHHT 1.0, we used the first difference method (FDM) (Peterson et al. 1998) using all available stations in each grid box. We modified the FDM to use backward differences instead of forward differences, so as to avoid errors due to sparsity of weather stations in the earliest years of the time series. The time series for a given grid box is calculated by the following equation:

$$\overline{y}_i = \frac{1}{n}\sum_{j=1}^{n}\delta_{i,j} \tag{1}$$

where $n$ is the number of stations, $\delta_{ij}$ is the first difference for the $j^{\text{th}}$ station at time point $i$, $\overline{y_i}$ is the first difference at time point $i$, and

$$\delta_{i,j} = X_{i-1,j} - X_{i,j} \tag{2}$$

According to Peterson et al. (1998), the FDM can introduce random errors owing to outliers at the endpoints of the series segments. Therefore, we used a similar "endpoint outlier trimming" scheme as in Peterson et al. (1998), to reduce the random errors. Then, the climate anomaly method (CAM) (Jones et al. 1986a, see also Jones and Hulme 1996) was used to average the grid

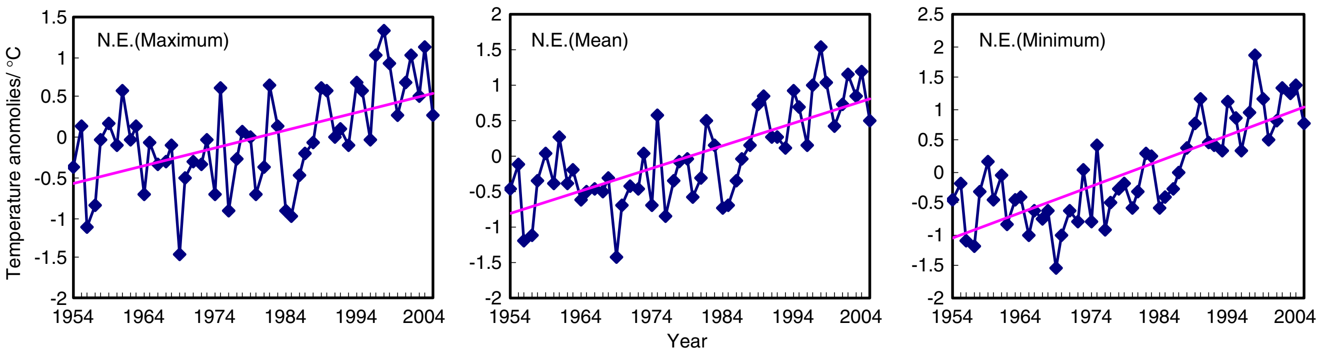


**Fig. 5** Anomalies of regional annual mean SAT (1954–2005)

series into regional series. Then, we repeated the entire process using the OWS network and again for the combined networks (i.e. both NSs and OWSs).

We developed regional annual mean temperature (MT) series for mainland China (Fig. 2). The warming trends (over 1961–2004) for the CHHT, OWS, and combined agree very well: the linear trends for the three series are: total: 0.280 C decade$^{-1}$, CHHT: 0.285 C decade$^{-1}$, and OWS: 0.253 C decade$^{-1}$, respectively. The trend detected by data from OWS only is slightly lower because the OWS anomaly during the 1960s was higher than that of the NS series. In the 1960s, the station numbers were increasing in the OWS network (Fig. 3). From the comparison, we conclude that CHHT 1.0 represents the whole region well. Because the data for the OWS have not been strictly quality controlled and homogenized, only the CHHT 1.0 dataset, which contains only NS, was used to detect the warming trends in Northeast China described below.

We focus on the area 35–55°N and 105–135°E, which is similar to the Northeast subregion from Wang et al. (2001), Li et al. (2004), and Tu (1984). We use the temperature data from 187 stations (Fig. 4) in this subregion from CHHT 1.0, and the data cover the period of 1954–2005.

**Table 1** Trends of MT in Northeast China over 1954–2005 (statistically significant at (asterisk) the 0.05 level and (double asterisk) at the 0.01 level)

| | Mean minimum | Mean | Mean maximum |
|---|---|---|---|
| Annual | 0.42** | 0.33** | 0.23** |
| Spring | 0.51** | 0.43** | 0.32** |
| Summer | 0.27** | 0.21** | 0.14** |
| Autumn | 0.31** | 0.24** | 0.13** |
| Winter | 0.65** | 0.50** | 0.37** |

## 3 Annual and seasonal trends of regional temperature

### 3.1 Annual temperature changes

We used the method of Li et al. (2004), which uses principal components (PC) as weighting factors when building regional averages. Figure 5 shows that in Northeast China the annual MT (mean *T*) had a clear upward trend (0.331 C decade$^{-1}$), the upward trend of annual mean minimum temperature (MMIT) (mean Tmin) (0.418 C decade$^{-1}$) is greater, and the upward trend of annual mean maximum temperature (MMAT) (mean Tmax) (0.218 C decade$^{-1}$) is less (Table 1). The warming took place mainly since the early 1980s, and the regional annual MT mainly showed negative anomalies before the 1980s, especially in the mid 1950s and the late 1960s. The coldest year was 1969, and the hottest year was 1998.

### 3.2 Seasonal temperature changes

Figure 6 shows the seasonal anomalies of SAT in Northeast China from 1954 to 2005. Each season has significant warming trends in MMIT, MT, and MMAT similar to the annual temperature. The warming trends of seasonal MMIT are the greatest, and those of MMAT are the lowest. The warming trends during winter and spring are greater than those of summer and fall. The regional winter temperature trend is the greatest. In the last 52 years, the MMIT, MT, and MMAT increased about 3.3 C, 2.6 C, and 1.9 C in winter, but for the summer, the temperature changes are much less, the changes being only 1.4 C, 1.1 C, and 0.7 C, respectively (Table 1).

Since the 1980s, the mean SAT anomaly of each season (Fig. 6) has been mainly positive, and the warmest years are 1998, 2000, 2005, and 2001. For the MMIT, the changes for the different seasons are slightly different: the MMITs of autumn and winter have shown mainly positive anomalies since the mid 1980s, whereas those for spring

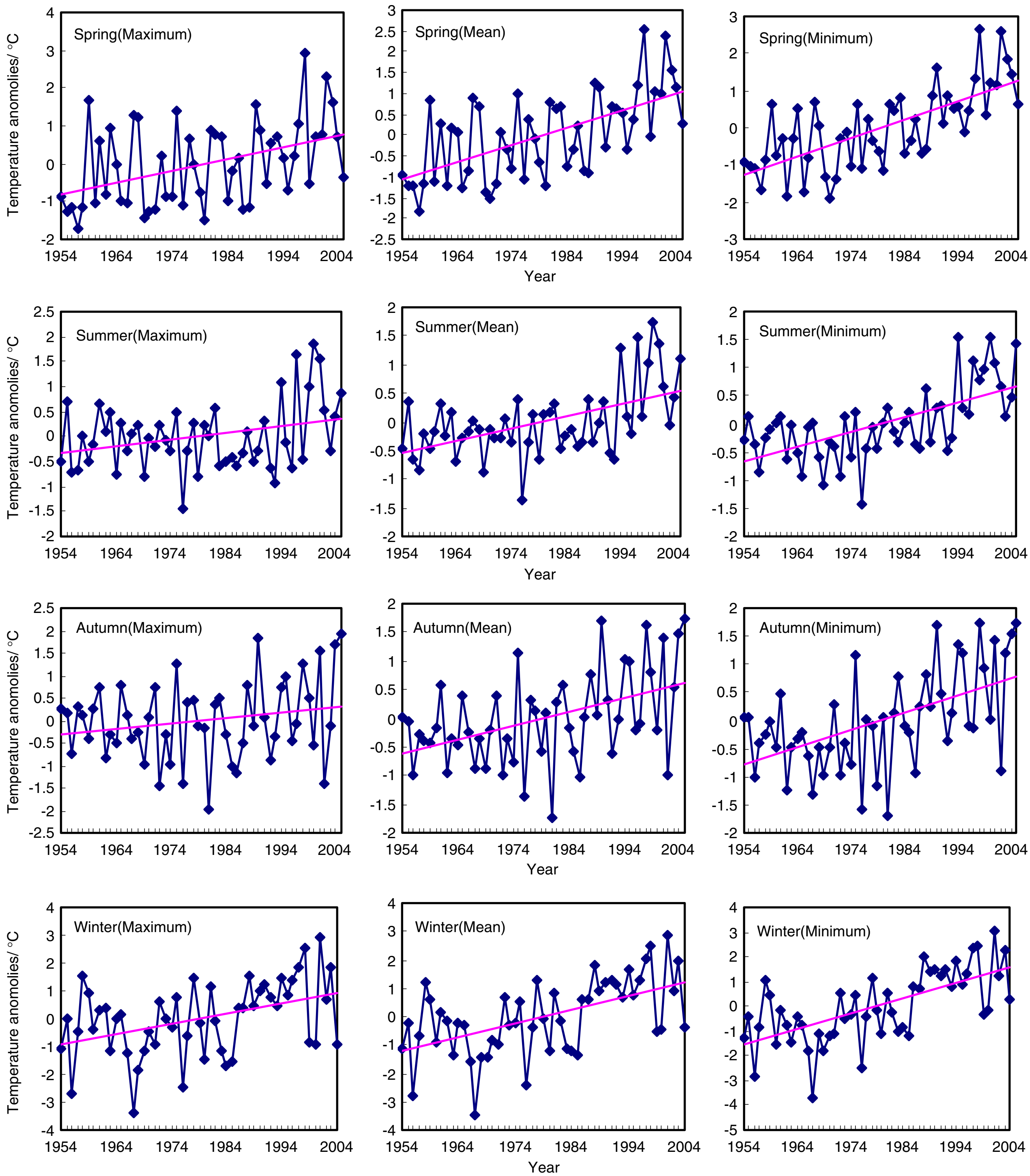


**Fig. 6** Anomalies of regional seasonal mean SAT 1954–2005

and summer only show this since the late 1980s or early 1990s; however, the warmest years match those for MT. MMAT shows similar contrasts (Fig. 6). The positive anomalies found in winter MMIT are the largest of all the seasons.

## 4 Impacts of UHI on Northeast China temperature changes

Although large impacts of land use changes have been found in previous papers (Zhang et al. 2003; Kalnay and

**Table 2** Trends of annual MT in Northeast China with and without typical heat island stations (1954–2005) (statistically significant at (asterisk) the 0.05 level and (double asterisk) at the 0.01 level)

| Annual mean air temperature(C) | With typical heat island stations (ºC decade$^{-1}$) | Without typical heat island stations (ºC decade$^{-1}$) | Difference (ºC decade$^{-1}$) |
|---|---|---|---|
| Mean minimum | 0.418** | 0.404** | 0.014 |
| Mean | 0.331** | 0.321** | 0.010 |
| Mean maximum | 0.226** | 0.218** | 0.008 |

Cai 2003; Zhou et al. 2004; He et al. 2007), and the UHI effect could be a part of these impacts, some of these studies have used reanalyses, which are subject to time-varying biases (Simmons et al. 2004), so the most reliable way to investigate possible urbanization biases is to compare rural and urban station series (Brohan et al. 2006).

We use the same methods to study the impact of UHIs in Northeast China as Li et al. (2004), and we use the comprehensive approach of Easterling et al. 1997and Li et al. 2004to classify the stations in the region. Each of the 187 stations was classified as either: (1) "typical heat island station" by the population of the cities and the location of the stations (the population is more than 500, 000, or, the population is more than 50,000 and the station site is urban) or (2) "Not typical heat island station" (the population is less than 50,000, or the population is between 50,000 and 500,000 and the station site is rural or suburban).

Based on this classification, we found the number of different types of stations in Northeast China; 58 of the 187 stations are classified into "typical heat island stations" (type 1), and the other 129 are classified into "not typical heat island stations" (type 2). The typical urban stations account for 31% of all the stations. This proportion is similar to the result of Li et al. (2004), while it is slightly less than the result of He et al. (2007) of nearly 40%. The reason is that we eliminate some medium-sized cities (populations from 50,000 to 500,000) from the "typical urban stations" class. Most of them are located in rural places (not far away from farm zones) but are marked as "suburb" or "countryside" in metadata files.

Tables 2 and 3 show the UHI effect on the annual and seasonal MT changes by the differences of the trend between the time series built with all the stations and with only non-typical heat island stations. For example, the annual MT warming trend in this region calculated with all 187 stations is 0.331 C decade$^{-1}$, it is 0.321 C decade$^{-1}$ when typical heat island stations are eliminated, and it is 0.348 C decade$^{-1}$ with the typical heat island stations, so the heat island effect on the annual MT warming should be 0.027 C decade$^{-1}$ (0.348 minus 0.321) during the last 52 years. In agreement with Li et al. (2004), the heat island effect on the annual MT warming trend is only about 8.2% (0.027 divided by 0.331) of the regional total warming in Northeast China. The impacts of heat island effect on annual MMAT and MMIT changes are also analyzed. As shown in Table 2, the larger one is the annual MMIT at about 0.014 C decade$^{-1}$, and the lesser one is the annual MMAT, at about 0.008 C decade$^{-1}$, with biases of about 3.5% and 3.7% of the total trends, respectively. It seems that the impact of heat island effect on annual MT changes is not significant.

Table 3 shows that, in the last 50 years, the seasonal UHI effects on the MMIT are the greatest and those on the MMAT are the least. The effects of UHIs are evident in the winter, spring, and autumn, and are greatest in winter. However, the UHI bias is less than 10% of the regional warming. In Li et al. (2004), the UHI bias on annual MT was calculated as −0.002 C decade$^{-1}$ for a similar region. Taking into account the differences in stations, time period, and randomness, this difference (0.010 C decade$^{-1}$) is acceptable, and both results indicate that the role of UHIs is secondary.

**Table 3** Regional seasonal MT trends (with and without "typical heat island effect" stations) in Northeast China (1954–2005) (ºC decade$^{-1}$) (statistically significant at (asterisk) the 0.05 level and (double asterisk) at the 0.01 level)

| | The mean minimum air temperature | | | The MT | | | The mean maximum air temperature | | |
|---|---|---|---|---|---|---|---|---|---|
| | With UHI | Non-UHI | UHI bias | With UHI | Non-UHI | UHI bias | With UHI | Non-UHI | UHI bias |
| Spring | 0.513** | 0.495** | 0.008 | 0.433** | 0.417** | 0.016 | 0.321** | 0.308** | 0.013 |
| Summer | 0.269** | 0.262** | 0.007 | 0.215** | 0.215** | 0.000 | 0.141** | 0.137** | 0.004 |
| Autumn | 0.315** | 0.309** | 0.006 | 0.243** | 0.240** | 0.003 | 0.128** | 0.126** | 0.002 |
| Winter | 0.652** | 0.631** | 0.021 | 0.502** | 0.492** | 0.010 | 0.374** | 0.370** | 0.004 |

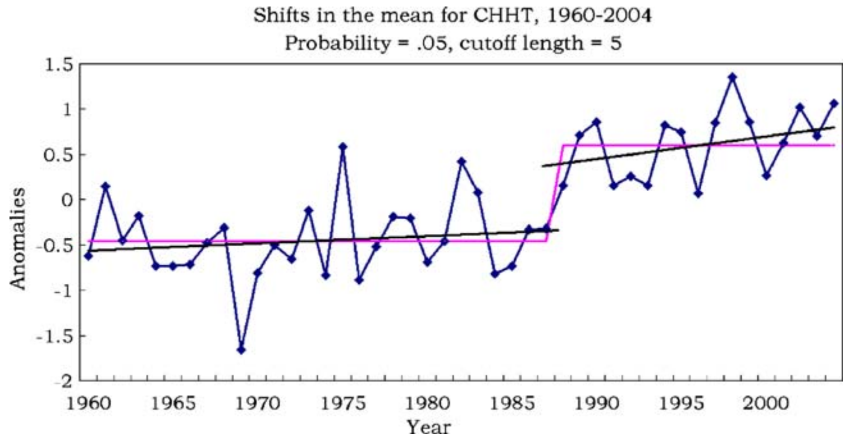


**Fig. 7** The abrupt change of the annual MT during 1960–2004

## 5 Discussion

Our evaluation of the UHI effect is much less than that of Ren et al. (2008). They used a smaller region (33°–43°N, 108°–120°E) and got an average warming trend of 0.18 C decade$^{-1}$ during 1961–2000 based on the 63 selected "rural" stations series, and they concluded that the UHI effect would be about 0.11 C decade$^{-1}$ (about 37.9% of the total warming regional warming trend of 0.29 C decade$^{-1}$). Our results are supported by previous analyses (Li et al. 2004; Jones et al. 1990). In their study, only 63 (less than 10%) stations from a total of 653 stations were selected as rural stations in Ren et al. (2008); and some of them had not been quality controlled and homogenized. In a recent study by Yan et al. (2009), homogeneity adjustments to the OWS stations decreased the UHI effect in Beijing by about 42% (from 80% in Ren et al. (2008) to 38% in Yan et al. (2009)). Further, the coherence between the warming trends detected by both networks (total network and OWS) proves that, for national scales, the introduction of the data from OWSs will not have much effect on estimates of regional climate warming trends in Mainland China; the differences between the two networks has been counteracted with increase of the station numbers.

Figure 7 shows, on an annual basis, that Northeast China underwent an abrupt warming of about 1.1 C around 1990. A sequential algorithm for testing climate regime shifts (regime shift analysis; see Appendix) (Rodionov 2004) shows that this is statistically significant at the 5% confidence level. Winter MT underwent a similar abrupt change. The abrupt warming is not likely to be a result of UHI effects or land use changes, with changes of atmospheric circulation being a more likely cause. The MT trend for 1960–1987 is 0.082 C decade$^{-1}$, and for 1988–2004, it is 0.341 C decade$^{-1}$, so the period-weighted average trend for 1960–2004 is 0.18 C decade$^{-1}$, suggesting that the abrupt change round 1988 accounts for about 51% of the total warming trend (0.368 C decade$^{-1}$ for 1960–2004). This finding supports our conclusion that UHI effects have a relatively minor contribution to the regional warming trend.

## 6 Conclusions

Based on homogenized land SAT data (CHHT 1.0) in China, the long-term urbanization effects on regional temperatures in Northeast China were analyzed, covering 1954–2005. We come to the following conclusions.

1. CHHT 1.0 represents regional temperature changes well: the introduction of the data from OWSs will not have much effect on estimates of regional climate warming trends in Mainland China.
2. Based on the homogenized dataset (CHHT 1.0), the warming of Northeast China is found to be much larger than in the global surface temperature record for the last century. In the last 52 years, regional annual MMIT, MT, and MMAT have increased by 2.1 C, 1.7 C, and 1.1 C, respectively. The MT warming of winter is greatest of all, with MMIT, MT, and MMAT increasing by 3.3 C, 2.6 C, and 1.9 C, respectively.
3. Comparing the regional MT trends with and without "obvious UHI stations," we evaluated the impact of the UHI effect. Though some studies show that the contribution of the urbanization may be great locally, the total contribution of UHI to large-scale trends is still limited, in accordance with many recent studies (Zhou et al. 2004; Li et al. 2004).
4. An obvious regime shift change is detected around 1988 in the regional temperature series in this paper, confirming that the significant warming trends during the period are not dominated by UHI effects.

**Acknowledgements** This paper has been supported by the National Natural Science Foundation of China (grant 40605021), National Key Technology R&D Program (2007BAC29B01-01) and the Ministry of Science and Technology of China through the based platforms special project of scientific data sharing system (grant 2005DKA31700-01).

The corresponding author would like to thank David Parker for many constructive suggestions during the corresponding author's visit to the Met Office Hadley Centre. Phil Jones has been supported by the U.S. Department of Energy (grant DE-FG02-98ER62601).

## Appendix

Methodologies of sequential regime shift detection method

Let x1, x2, ..., x*i*, be a time-series with new data arriving regularly. When a new observation arrives, a check is performed to determine if it represents a statistically significant deviation from the mean value of the current regime. If it does, that year is marked as a potential change point $c$, and subsequent observations are used to confirm or reject this hypothesis. The hypothesis is tested using the regime shift index (RSI), which is calculated for each $c$:

$$\mathrm{RSI}_c = \sum_{i=c}^{c+m} \frac{x_i^*}{l\sigma_l},$$

where $m$=0,1..., $l-1$ (i.e., number of years since the start of a new regime), $l$ being the cut-off length of the regimes to be tested, and $\sigma_1$ is the average standard deviation for all 1-year intervals in the time series. RSI represents a cumulative sum of normalized deviations $x_i^*$) from the hypothetical mean level for the new regime ($\overline{x_{\mathrm{new}}}$), for which the difference, diff, from the mean level for the current regime ($\overline{x_{\mathrm{cur}}}$) is statistically significant according to a Student's $t$ test:

$$\mathrm{diff} = \overline{x_{\mathrm{new}}} - \overline{x_{\mathrm{cur}}} = t\sqrt{2\sigma_l^2/l},$$

where $t$ is the value of the $t$ distribution with $2l-2$ degrees of freedom at the given probability level $p$. If, at any time from the start of the new regime, RSI becomes negative, the test fails and a zero value is assigned. If RSI remains positive throughout $l-1$, then $c$ is declared to be the time of a regime shift at the level $\leq p$. The search for the next regime shift starts with $c+1$ to ensure that its timing is detected correctly even if the actual duration of the new regime is <l year.

In a previous version of the program, Rodionov (2004) used a running window of a fixed size equal to 2*l* (i.e. [$c-l$, $c+l$], centered at $c$). In this case, the average value for the current regime $\overline{x_{\mathrm{cur}}}$ is calculated for the period ($c-l$, $c$). If a transition from one regime to another is gradual, the program might not detect it because $\overline{x_{\mathrm{cur}}}$ is also changing as the window slides along the time axis, so the difference between the new arriving observations and $\overline{x_{\mathrm{cur}}}$ may not be statistically significant to become a potential change point and trigger the calculation of RSI. In the new version used here, $\overline{x_{\mathrm{cur}}}$ is calculated for the period from the previous regime shift to the point immediately before the current point in time. As a result, a stepwise function of regimes is produced in almost all cases, whereas the previous version of the program could detect abrupt regime shifts only. To improve the performance at the beginning of the time series, the testing for a regime shift starts not from $x_{l+1}$, as in the previous version, but from $x_2$. The average value $\overline{x_{\mathrm{cur}}}$ is still calculated for the entire initial period [1, *l*], but if a regime shift occurred prior to $i=l$, it is detected.

## References

Brohan P, Kennedy J, Harris I, Tett SFB, Jones PD (2006) Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. J Geophys Res 111:D12106. doi:10.1029/2005JD006548

Easterling DR, Horton B, Jones PD et al (1997) Maximum and minimum temperature trends for the global. Science 227:364–367

Feng S, Hu Q, Qian W (2004) Quality control of daily meteorological data in China, 1951–2000: A new dataset. Int J Climatol 24:853–870

Gallo KP, Easterling DR, Peterson TC (1996) The influence of land use/land cover on climatological values of the diurnal temperature range. J Climate 9:2941–2944

Gallo KP, Timothy WO, Easterling DR et al (1999) Temperature trends of the U.S. historical climatology network based on satellite-designated land use/land cover. J Climate 12:1344–1348

Hansen JR, Lebedeff S (1987) Global trends of measured surface temperature. J Geophys Res 92(13):13345–13372

He J, Liu J, Zhuang D et al (2007) Assessing the effect of land use/land cover change on the change of urban heat island intensity. Theor Appl Climatol 90:217–226

Houghton JT, Ding Y, Griggs DJ et al (2001) Contribution of working group I to the third assessment report of the intergovernmental panel on climate change. In Climate Change 2001: The Scientific Basis, eds. University of Cambridge

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

Jones PD, Raper SCB, Bradley RS et al (1986a) Northern hemisphere surface air temperature variations: 1851–1984. J Appl Met 25:161–179

Jones PD, Raper SCB, Wigley TML (1986b) Southern hemisphere surface air temperature variations: 1851–1984. J Appl Met 25:1213–1230

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

Jones PD, Groisman PYA, Coughlan M, Plummer N, Wang W-C, Karl TR (1990) Assessment of urbanization effects in time series of surface air temperature over land. Nature 347:169–172

Kalnay E, Cai M (2003) Impact of urbanization and land-use change on climate. J Nature 423(6939):528–531

Karl TR, Diaz HF, Kukla G (1988) Urbanization: its detection and effect in the United States climate record. J Climate 1:1099–1123

Li Q (2006) The contribution of UHI effect to the China surface warming: Since 1954 and since 1979, 2006, Abstract of Western Pacific Geophysics Meeting (Invited presentation in WPGM2006)

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

Li Q, Zhang H, Chen J, Li W, Liu X, Jones PD (2009) A mainland China homogenized historical temperature dataset of 1951–2004. Bull Am Meteo Soci. doi:10.1175/2009BAMS2736.1

Ma L, Zhang T, Li Q, Frauenfeld OW, Qin D (2008) Evaluation of ERA-40, NCEP-1, and NCEP-2 Reanalysis Air Temperatures with Ground-based Measurements in China. J Geophys Res 113: D15115. doi:10.1029/2007JD009549

Parker DE (2004) Large-scale warming is not urban. Nature 432:290–290

Parker DE (2006) A demonstration that large-scale warming is not urban. J Climate 19:2882–2895

Peterson TC (2003) Assessment of urban versus rural in situ surface temperature in the contiguous United States: No difference found. J Climate 16:2941–2959

Peterson TC, Karl TR, Jamason PF, Knight R, Easterling DR (1998) First difference method: Maximum station density for the calculation of long-term global temperature change. J Geoghy Res 103:25967–25974

Ren G, Chu Z, Chen Z et al (2007) Implications of temporal change in urban heat island intensity observed at Beijing and Wuhan stations. Geophys Res Lett 34(5):L05711 (1–5)

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

Rodionov SN (2004) A sequential algorithm for testing climate regime shifts. Geophys Res Lett 31(5):L09204 (1–4)

Simmons AJ, Jones PD, da Costa Bechtold V, Beljaars ACM, Kållberg PW, Saarinen S, Uppala SM, Viterbo P, Wedi N (2004) Comparison of trends and low-frequency variability in CRU, ERA-40 and NCEP/NCAR analyses of surface air temperature. J Geophys Res 109:D24115. doi:10.1029/2004JD006306

Trenberth KE, Jones PD, Ambenje P et al (2007) Observations: surface and atmospheric climate change. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. In climate change 2007: The physical science basis, eds. University of Cambridge

Tu Q (1984) The trends and periodicity of temperature change in China during recent 100 years. J Nanjing Inst Meteorol 7:15–30 (in Chinese)

Vinnikov KY, Groisman PY, Lugina KM (1990) Empirical data on contemporary global climate changes (temperature and precipitation). J Climate 3:662–677

Wang S, Ye J, Gong D, Zhu J, Yao T (1998) Construction of mean annual temperature series for the last one hundred years in China. Q J Appl Meteorol 9:396–401 (in Chinese)

Wang T, Wu W, Xue X et al (2004) the special and temporal changes of the desertaztion land in North Chian during recent 50 years. Acta Geogr Sin 59:203–212

Wang X, JuLian L, Gaffen DJ (2001) Late-Twentieth-Century climatology and trends of surface humidity and temperature in China. J Climate 14:2833–2845

Yan Z, Li Z, Li Q, Jones PD (2009) Effects of site-change and urbanisation in the Beijing temperature series 1977–2006. Int J Climatol (in press)

Zhai P, Chao Q, Zou X (2004) Progress in China's climate change study in the 20th century. J Geograph Sci 21(z1):3–11

Zhang J, Dong W, Ye D et al (2003) New evidence for effects of land cover in China on summer climate. Chin Sci Bull 48:401–405

Zhou LM, Dickinson RE, Tian YH, Fang JY, Li QX, Kaufmann RK (2004) Evidence for a significant urbanization effect on climate in China. Proc Natl Acad Sci USA 101:9540–9544

Zhou S, Su J (1994) Urban climatology. Meteorological Press, Beijing, p 244