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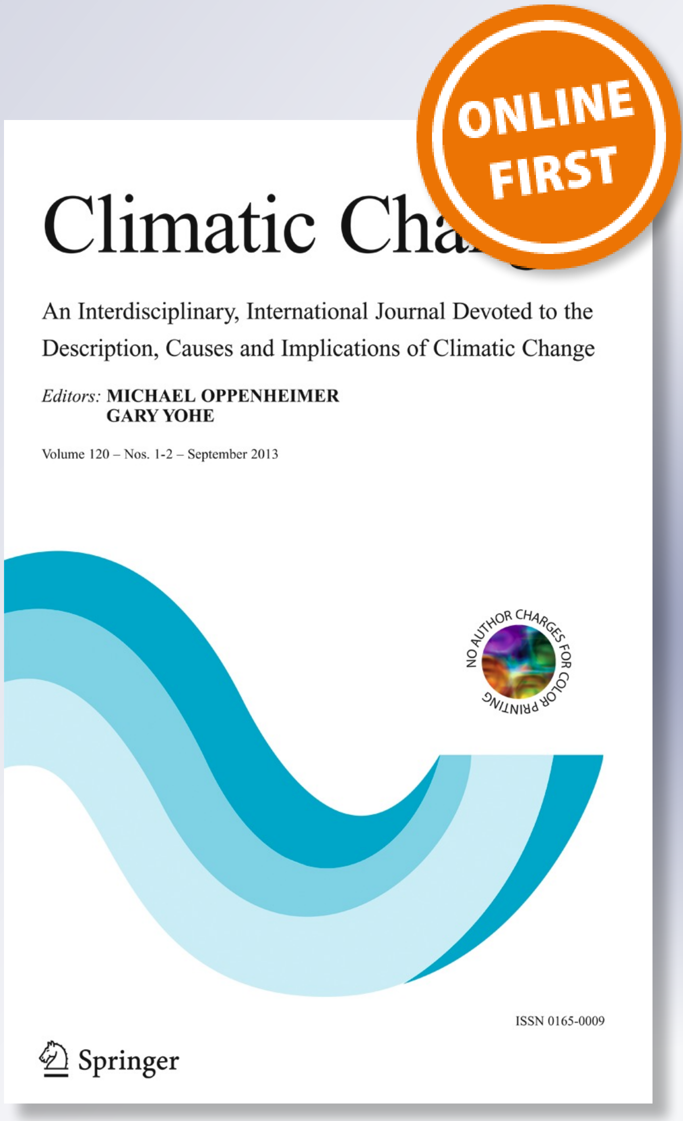

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Abstract This paper provides new evidence of regional warming trends from local Chinese observations covering the period 1951–2010. We used satellite-derived land data and weighted urban and rural temperature records (a weighted method) and estimate the regional warming trend, which involves natural climate change and human impact. The annual warming rate over the whole of China is 0.21±0.02 °C/decade. The seasonal warming is 0.30±0.05 °C/decade (Winter), 0.24 °C±0.03 °C/decade (Spring); 0.16±0.02 °C/decade (Summer) and 0.21±0.03 °C/decade (Autumn). The mean warming trend is lower than previous estimates (e.g. NMIC, CRU-China) using un-weighted methods (arithmetic average of all records). The warming difference between the weighted and un-weighted accounts for 27 % (12 %) of the NMIC (CRU-China) un-weighted estimate on the total warming. This indicates that previous estimations overestimated a regional warming trend. The differences can be partly attributed to the weighting of the urban effect which is taken into consideration in this study, resulting in a much slower temperature increase. Spatially, the northern part of China shows a larger difference than the south especially for winter and spring. We argue that it is of importance to take into consideration the influence of urban land-use change to improve the physical understanding of surface warming in China over past decades.

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Abbreviations

CAM	Climate Anomaly Method
CAS	Chinese Academy of Sciences
CE	Coefficient of Efficiency
CMA	China Meteorological Administration
CRU	Climatic Research Unit
FDM	First Differences Method
GCPs	Ground Control Points
GISS	Goddard Institute for Space Studies
NASA	National Aeronautics and Space Administration
NMIC	National Meteorological Information Centre
P-E	Peterson and Easterling
RE	Reduction of Error
RSM	Reference Station Method
SAT	Surface Air Temperature
SD	Standard Deviations
SE	Sampling error
UHI	Urban Heat Island

1 Introduction

Global warming is an important issue for climate change research. In examining the warming trend over recent decades, how to use local point observations to estimate large-scale mean trends is of particular importance. Meteorological observations are local, no matter at urban or rural stations. The purpose of this study is to provide a reliable regional warming trend over the past 60 years over China using more than 700 meteorological stations and satellite observed land-use data.

In various studies, the local station data are converted to regular grids and then averaged to produce a regional mean temperature series (Smith et al. 2008; Hausfather et al. 2013; Quayle et al. 1999; Zhang and Li 1982; Tang and Ding 2007; Li et al. 2009; Zhang et al. 2010). At grid cell, station records can be combined and converted into anomalies through the Climate Anomaly Method (CAM) (Jones 1994; 2012; Brohan et al. 2006), the Reference Station Method (RSM) (Hansen et al. 2001), and First Differences Method (FDM) (Peterson et al. 1998). However, if all stations including the large cities are used, the warming trend is usually exaggerated. For example, let us assume there are five stations in one grid box, two urban and three rural stations. Then the two urban stations will represent 40 % of this grid if all stations data are arithmetically averaged, but the scale of the city is often limited in a small portion because the urban area only accounts for a small part of continent. In China, urban land area accounts for only 0.67 % of the total land areas (see Section 3.2, estimated according to the satellite data (Vogelmann et al. 2001)). Therefore, average temperatures for all stations without weighting will overestimate the urban impact on temperature trends. Tang and Ding (2007) reported of a regional warming trend of 0.23 °C/decade for China from 1951–2007 using 5°×5° spatially resolved data from 616 stations. Li and Li (2007) showed 0.23–0.25 °C/decade warming trend for China from 1951–2004 with 2.5°×2.5° spatial resolution using 728 stations and FDM method.

In some studies on Urban Heat Island effect, the data of some urban stations are usually neglected (Hansen et al. 2010; Peterson and Owen 2005; Zhou et al. 2001; Wang et al. 1990;

Zhang et al. 2010; Ren and Ren 2011; Li et al. 2004; Hua et al. 2008; Ren et al. 2008; Yang et al. 2011 and Wang and Ge 2012). It provides a rural series without urban impact on average temperature trend. Zhang et al. (2010) estimated a rural warming trend of 0.20 °C/decade for China over 1961–2004 using 138 reference stations. Jones et al. (2008) showed a 0.15 °C/decade rural warming over 1951–2004 for eastern China by comparing land surface air temperature (SAT) with sea surface temperature from adjacent sea areas. Yang et al. (2011) showed a rural warming of 0.50 °C/decade from 1981–2007 for eastern China using satellite night-light index. The rural regional trend shows regional response to global warming, which removes the urbanization effect induced by human activity. In our study, the impact of human activity is not removed and the urbanization effect is included in the regional temperature trend to estimate an actual SAT change.

This paper provides new estimates of average annual and seasonal warming trends of China by using meteorological observations covering the period of 1951–2010. We apply weighted averaging of urban and rural records to provide a regional mean temperature series. New estimate will be provided on the warming over the past 60 years, which includes natural climate change and human impacts (including greenhouse effect and urbanization effect).

2 Temperature data

2.1 Station data

Temperature data are obtained from the "Monthly Surface Climate Dataset in China" of the China Meteorological Administration (CMA) (available at http://www.cma.gov.cn/2011qxfw/2011qsjgx/). Overall, 728 meteorological stations including the national reference climate stations and basic meteorological stations are selected. Due to instrument changes, station relocations, and alternations, some stations were removed, and some were added. 670 stations are currently in operation. Of these stations, 63 were eliminated due to the lack of data for more than 10 years. Finally, 607 stations are selected (Supplementary Fig. 7). The data cover the period 1951–2010. The pre 1951 data include strong inhomogeneities due to the lack of uniform measurement standard. From 1950 on, when the People's Republic of China just established, most stations began to put to use regularly.

2.2 Quality control and homogenization

A quality control of the temperature data is performed by the National Meteorological Information Centre (NMIC), CMA. These quality control methods include synoptic cross-validations and validations of climatological characteristics (e.g., annual spatial distribution, seasonal spatial distribution, annual trend distribution, seasonal trend distribution, inter-annual mean temperature contrast, and correlations). Some of the possible erroneous records such as the extreme singular value are also ruled out and the data are of good quality.

The homogenization method is that of Peterson and Easterling (1994) and Easterling and Peterson (1995), which is also performed by the NMIC team (Li et al. 2009). In the homogenization exercise, obvious discontinuous time-series, caused by instrument changes, station moves or different observing practices, were adjusted after they were combined with the station metadata. The details can be found in the Supplementary 1.

2.3 Treatment of missing data

Missing monthly station values account for 6 % of the total records. They are generally in the earlier years. The missing values are estimated using linear interpolation of data from the neighboring stations. The cross-validation tests are used to evaluate the statistical fidelity of the regression models. The details can be found in the Supplementary 2.

3 Land use data

3.1 Source

The land use database is developed by the Chinese Academy of Sciences (CAS). The original data were derived from satellite remote sensing data provided by the US Landsat TM/ETM images which have a spatial resolution of 30 by 30 m (Vogelmann et al. 2001). These have been aggregated by CAS into 100 by 100 m picture elements ('pixels') (Liu et al. 2002; 2005). We use the period selected from 1980 onwards. The details are provided in Supplementary 3.

For the pre 1980 period, there is no satellite land data and therefore the paper maps of China including land information from aerial survey in 1950s and 1970s are used. The paper maps were made by the Surveying and Mapping Bureau of Chinese People's Liberation Army General Staff and are obtained from National Administration of Surveying, Mapping and Geoinformation. The scales of the maps are 1:50,000. Each map represents a small part of China with 10′x15′ latitude-longitude range and ten thousands more of maps compose the national information. From these paper maps, we can identify the urban land areas.

3.2 The urban land-use criteria

The urban land-use expansion is the significant feature of urbanization. Urban land-use types include urban built-up land and other industrial land uses in large, medium and small cities and towns (see Supplementary 3). Supplementary Fig. 5a presents the recent urban land-use coverage, which is 0.67 % of the total area of China. Supplementary Fig. 5b shows the increase in urban land use since 1980. Overall, urban land use has increased significantly, especially in eastern China.

4 Methods

4.1 Gridding methods

The station data is converted to a grid product because of the uneven distribution of stations. When gridding, all stations in the grid box were usually averaged arithmetically (unweighted), and urban scale in each grid was not considered. They usually exaggerate the average regional warming trend (Brohan et al. 2006; Jones et al. 2012; Tang and Ding 2007).

The current study estimates the scale of urban land and gives the grid temperature trend using the following method:

First, we calculate the temperature anomalies monthly, seasonally and annually for each station over the 1951–2010 period. The reference period is 1951–1980. We also refer to Hansen et al. work from NASA/GISS, they always use the 1951–1980 reference period instead of 1971–2000 or 1961–1990. Second, before all station data are converted to a regular grid, the distribution and range of urban and rural land use are identified. Third, based in the ratios of different land types within each grid, weights for the different stations (urban and rural, see Section 4.2 and Supplementary 4 for the selection criteria) are calculated within each grid. The urban land percentage is as weight of urban temperature and the rural land percentage is the weight of rural temperature in the same grid. Fourth, in the grid with two or more urban (or rural) stations in the same grid, the grid value for urban (or rural) area is the mean of all available urban (or rural) station values. In grids without a station, the nearest station data are used to interpolate. Fifth, the grid temperatures are obtained using the weighted-average method. Finally, the national mean temperature is calculated using the area-weighted average method based on the cosine of the latitude.

Classification of meteorological stations into urban or rural types always relies on an urban development (social environment) index such as population, night lighting, vegetation index and remote sensing thermal field, etc. (e.g. Hansen et al. 2010; Peterson and Owen 2005; Zhou et al. 2001; Ren and Ren 2011; Hausfather et al. 2013). However, these indexes usually represent environmental change only indirectly. We use urban land use as the index of urbanization, because it directly represents urban environmental change and the land dataset has high spatial resolution (100 m × 100 m) and wide coverage. The detailed division method of urban and rural stations is discussed in Section 4.2.

A small-sized grid (e.g. 1°×1°, 0.5°×0.5°) for China will result in too many missing data due to unequal distribution of stations; therefore, we choose a 2.5°×2.5° latitude-longitude grid. The number of grid points is 203 (lat:2.5°~55°N, lon:72.5°~135°E).

Due to the lack of satellite land data prior to 1980 we refer to the paper land maps of China from aerial survey in 1950s and 1970s. These maps are mainly used to provide the land information surrounding all stations, which can be helpful to identify urban stations or rural stations. Yet the weights of urban and rural areas in grid-box for the pre 1980 period are replaced by the values of 1980s. That is because the exact number of urban and rural areas in each grid for the 1950s–1970s is difficult to obtain from the ten thousands of paper maps considering that too much paper maps with a size of 10′x15′ latitude-longitudes are difficult to be digitalized and be aggregated into one national map. That is also because the total urban land use area is only a very small portion of the whole of China (less than 1 %), negligible especially for the pre 1980 period. The period of 1951–1980 is just before the rapid increase in urbanization of China, at that time urban development and the urbanization effect were minimal and there was little change in urban land use.

4.2 The urban and reference stations criteria

To divide the stations into urban or rural types, we extract land data from the area immediately surrounding a given meteorological station, rather than from an entire city. The details can be seen in the Supplementary 4. The result indicates that 95 % of all stations have experienced significant urban land-use expansion in their surroundings. Therefore, it is difficult to select adequate numbers of reference stations that are free from urbanization effects overall of China. Stations with the least urban land use are regarded as such reference stations. Supplementary Fig. 7 shows the distribution of urban and reference stations. There are 196 reference stations and 411 urban stations.

5 Results and discussions

5.1 New land-weighted average series analyses

Figure 1a shows the annual mean temperature time-series of China, which is calculated based on the land-weighted method using all urban and rural station data (henceforth referred to as the 'this study'). The black line represents the optimal estimate (the mean value). The color curves give the 95 % uncertainty range due to various error components (the detailed methods are described in Supplementary 5). The uncertainty related to the temperature time-series is larger at the beginning of the 1950s due to the limited number of stations and their quality. As the number of stations has increased, this uncertainty gradually decreases, and the uncertainty is stable after the 1960s. The sampling error (green in Fig. 1a) has the largest uncertainty and the imputation error (part of red in Fig. 1a) is the least important error. The color straight lines represent the linear fitted trends in different periods adopting the least square method.

In general, the annual mean temperature of China increased 1.28±0.12 °C over the last 60 years with a stronger increase over the past 3 decades (1.18±0.18 °C).

The peak temperature was reached in 2007, and the second highest temperature occurred in 1998. Over the last 14 years, the mean temperature of China remained on a high level. Figure 1b–e show the seasonal temperature variations. The fluctuation of temperature is strong and the average warming trend is largest in winter, followed by spring, autumn and summer. The linear trends for the four seasons over the period 1951–2010 are as follows: 0.30±0.05 °C/decade (t=5.725, P=0.000, winter), 0.24±0.03 °C/decade (t=7.228, P=0.000, spring), 0.16±0.02 °C/decade (t=6.502, P=0.000, summer), 0.21±0.03 °C/decade (t=6.233, P=0.000, autumn).

5.2 Comparisons with other unweighted-average series

The average-unweighted series refer to the series using simply average of urban and rural stations data in each grid box. In Section 5.2.1, we compare the difference between this study, NMIC series, CRU-China series, and Tang series (Tang and Ding 2007). Table 1 provides detailed information of these series.

The NMIC grid series was produced and published in 2007 by national meteorological services from the National Meteorological Information Centre, CMA. The series data (http://www.cma.gov.cn/2011qxfw/2011qsjgx/, in Chinese) are representative of the temperature in China because it is made by national meteorological services. The homogenized station data of NMIC series are the same as that of this study. The gridding method of NMIC series is different compared to this study. The NMIC grid data are obtained by using the arithmetic average temperature from all stations in each grid and the interpolation using the modified Kriging method in grid without station. In the Tang et al. series, 616 stations are included and the temperature data are quality controlled but not homogenized (Tang and Ding 2007). The grid data are calculated through the arithmetic average temperature from all stations using the mean temperature from the highest and lowest mean temperatures. The CRU series are from CRU TS3.1 data (which can be found on the website http://badc.nerc.ac.uk/data, Harris et al. 2013). 109 stations are included in the CRU-China series and the temperature data were adjusted through a homogenization method (Jones et al. 1985). The grid data are obtained by the arithmetic average temperature from all stations in grids with station and the interpolation using the CAM method in grid without station. In this section, we compare and analyze the difference of results between these series.

5.2.1 Annual trend

Figure 2a shows the comparison of annual temperature change between our new series with those from CRU, NMIC and Tang series for 1951–2007. Before the mid-1970s, the variation of these series is consistent. From around 1980, the temperature increase reported by the

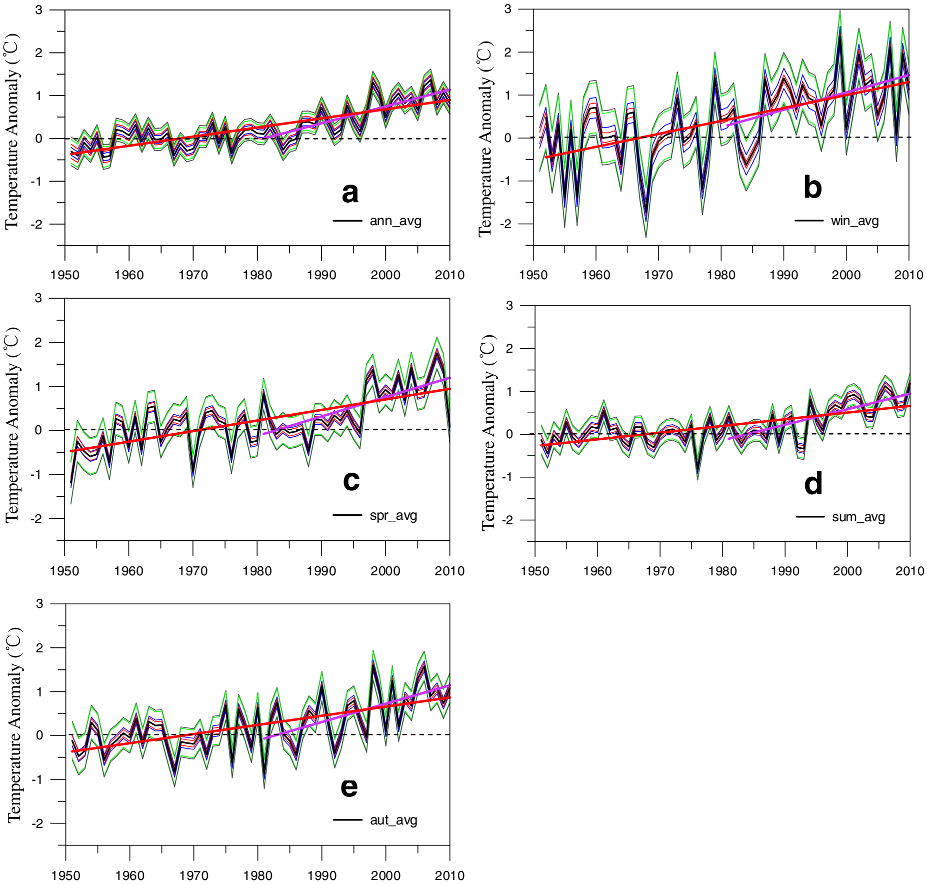

Fig. 1 Annual and seasonal mean temperature anomalies (wrt 1951–1980) for the whole Chinese mainland. In Fig. a, the *black line* is the best estimate value; the *red line* gives the 95 % uncertainty range caused by station and imputation errors; the *blue* and *green lines* give the 95 % error ranges due to interpolation error and sampling error respectively; the *grey lines* give the 95 % uncertainty range due to all errors; the color *straight lines* are the linear fits in different periods. **b**–**e** as a) but for the single seasons

CRU, NMIC and Tang series gradually becomes higher than that reported by our series. The systematically lower values in this study from approximately 1980 onwards are related to the Reform and Opening Up policy in China, rapid economic development and a lot of urban constructions. Table 1 shows the annual temperature trends of the different series. We select two time ranges (1951–2007; 1955–2007) to compare the temperature trends. Compared with the NMIC series, the temperature increase of our series is lower 0.38 °C/53a between 1955–2007, and 0.45 °C/57a between 1951–2007. The comparison with the Tang series (2007) indicates that the increase of our series is lower 0.23 °C/53a between 1955–2007, and 0.097 °C/57a between 1951–2007. Compared with the CRU-China series, the temperature increase of our new series is lower by 0.35 °C/52a between 1955–2006, and 0.26 °C/56a between 1951–2006. For 1951–1954, divergence between the curves is evident and the reason is most likely related to the different dataset and methods used to calculate mean temperature. Figure 2b shows the differences between the new series and the other three series. This indicates that prior to the mid-1970s, the difference is small and after 1970s the

Table 1 Information on published temperature series from China and trend results for different periods

Series	Time range	Trend (°C/decade)	Station	Data summary	Resolution	Gridding method
New Series	1951–2010	0.213*	607	Quality Control, Homogenization using P-E method	Gridding,,2.5°×2.5°	Grid with station: the land-weighted average T from urban and rural stations;
	1951–2007	0.212*				Grid without station: interpolation using the nearest station data.
	1955–2007	0.217*				
NMIC Series	1951–2007	0.290*	731	Quality Control, Homogenization using P-E method	Gridding,,1°×1°	Grid with station: the arithmetic average T from all stations;
	1955-2007	0.288*				Grid without station: interpolation using the modified Kriging method
Tang Series	1951–2007	0.229	616	Quality Control	Gridding,,5°×5°	Use the mean temperature from the highest and lowest mean temperatures;
	1955–2007	0.260				Gridding method: the arithmetic average T from all stations.
CRU-China Series (from CRU TS3.1)	1951–2007	0.241*	109	Quality Control, Homogenization using the method of Jones et al. (1985)	Gridding, 0.5°×0.5°	Grid with station: the arithmetic average T from all stations;
	1955–2007	0.266*				Station combination method: Climate Anomaly Method (CAM) (Jones 1994); Grid without station: interpolation using the method in Harris et al.(2013)

* stands for a significant trend with 99 % level. Data without * are cited from the reference

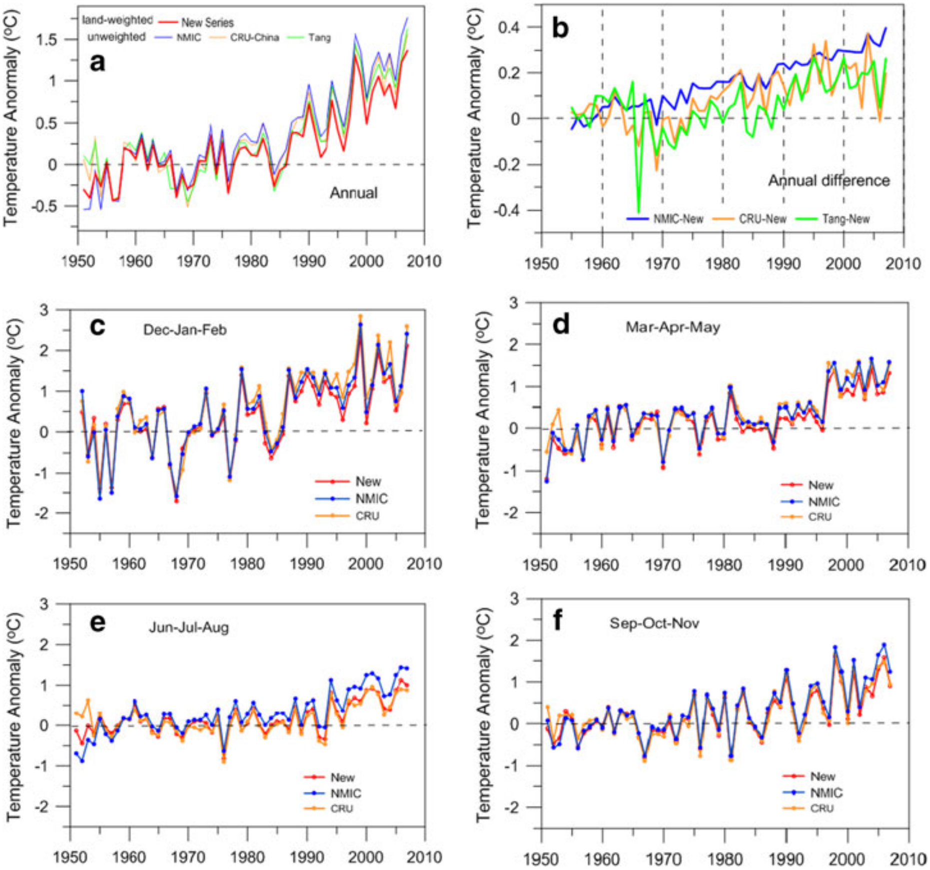

Fig. 2 Comparisons of the mean temperature series (land-weighted average and unweighted average). **a** annual temperature anomaly series, red-land-weighted, other colors-unweighted. **b** annual difference between these time series. **c**–**f** as a) but for seasonal series

difference gradually increases. However, the difference value grows up in fluctuation (shown in Fig. 2b), not smoothly, like temperature fluctuation as shown in Fig. 2a.

Figure 3 shows the distribution of the annual temperature trends with each grid for the new series, NMIC series and CRU series. Figure 3a-c, d-f, g-i display the temperature trend distributions of our new series (NMIC, CRU) across the different time ranges between 1951–2007. In general, the characteristics of the regional differences in our temperature series are similar to that of the NMIC and CRU series (e.g., the temperature change in China was higher in the north than in the south). However, the trends in our new series are smoother in the regional data compared to the other two series. This might be due to the method of gridding the temperature from the stations, the weighting of the urbanization effect results in a much slower temperature increase rate. To better analyze regional differences, we divide the country into five zones based on the China climate division scheme (Zheng et al. 2010): the Northeast Zone, the Huabei Zone, the Southeast Zone, Northwest Zone, and the Qinghai-Tibet Zone. For the grid at the border of two zones, it is defined into the zone which covers the majority of grid. Figure 4(left) shows the regional scales of three annual series curves with regard to the different zones. Before the 1980s, the linear trends for our new series are similar to those of the NMIC and CRU series for all the

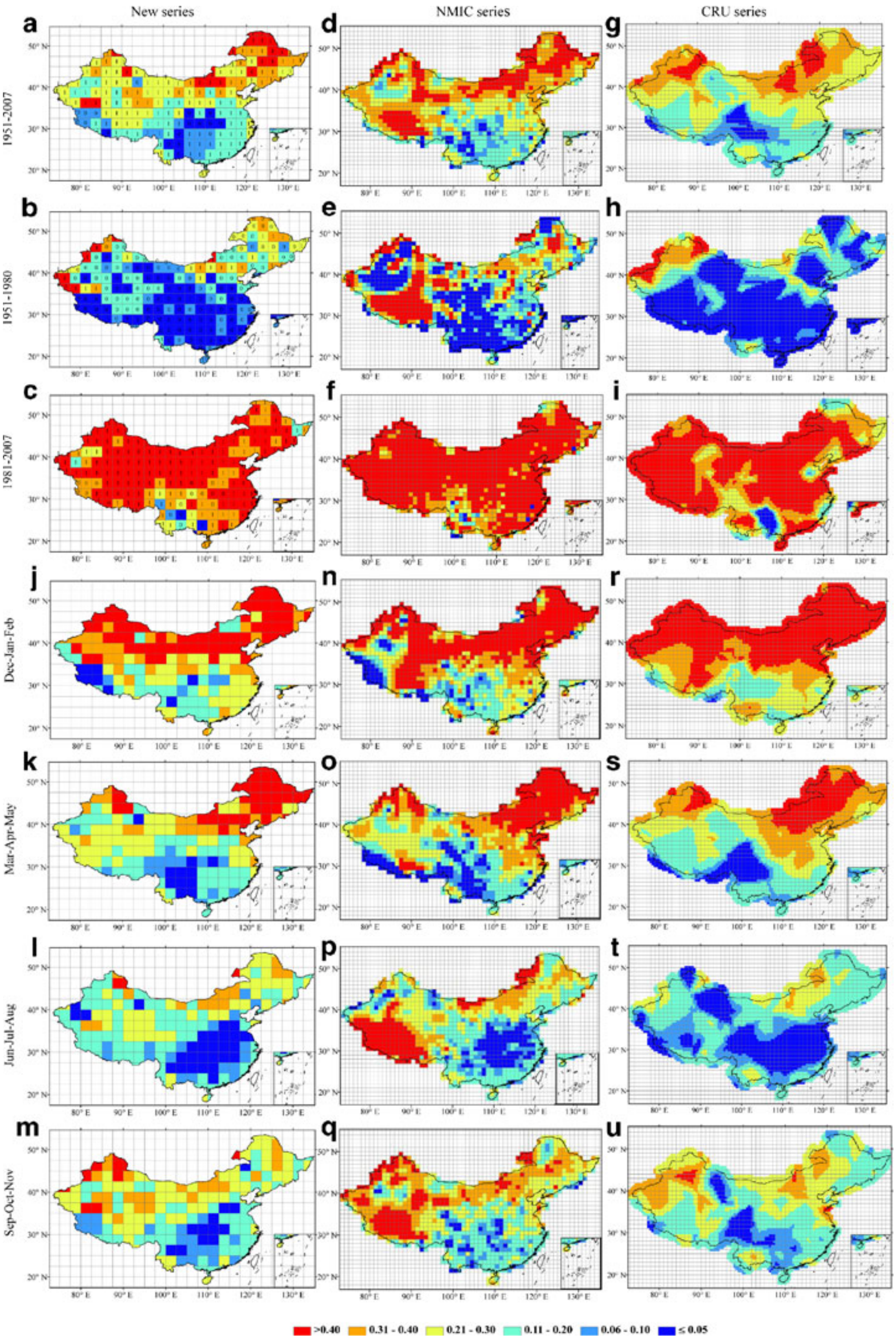

Fig. 3 National maps of annual and seasonal temperature trends of China over the last 57 years. Unit: °C/decade. (left) our new results, the grid points with 1 show as stat sig. trend at the 95 % level (0- insignificant); (*middle*) as **a**–**c** and **j**–**m** but for NMIC, (*right*) as **a**–**c** and **j**–**m** but for CRU

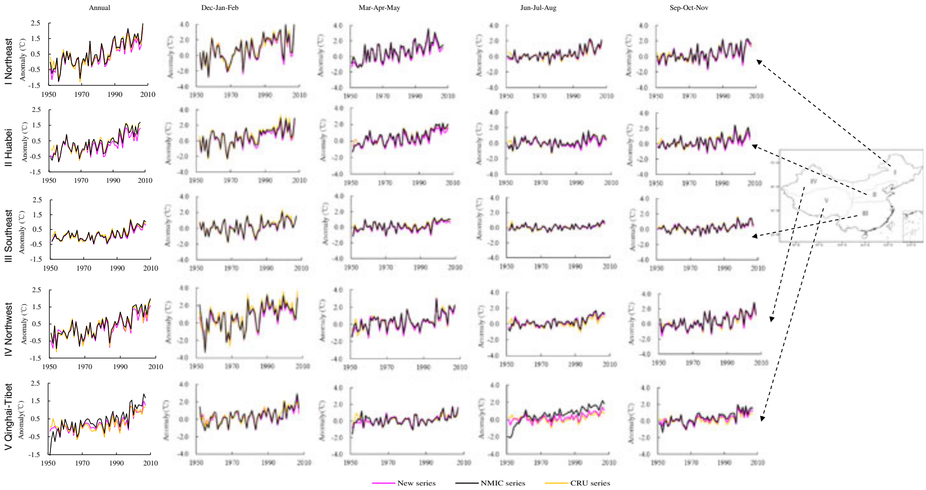

Fig. 4 The regional annual and seasonal temperature series in China over 1951–2007. The anomalies are presented with respect to the 1951–1980 reference period

zones. Over time, the annual temperature increase trends in the NMIC and CRU series are greater compared to our results, especially after the 1980s. Note that the annual temperature anomaly of the Qinghai-Tibet Zone from NMIC series between 1951–1954 is very small; this finding results from fewer available observational data. The Kriging method used by NMIC series was applied to the data from the other regions to interpolate missing data. Therefore, the estimated value might be lower than the real temperature.

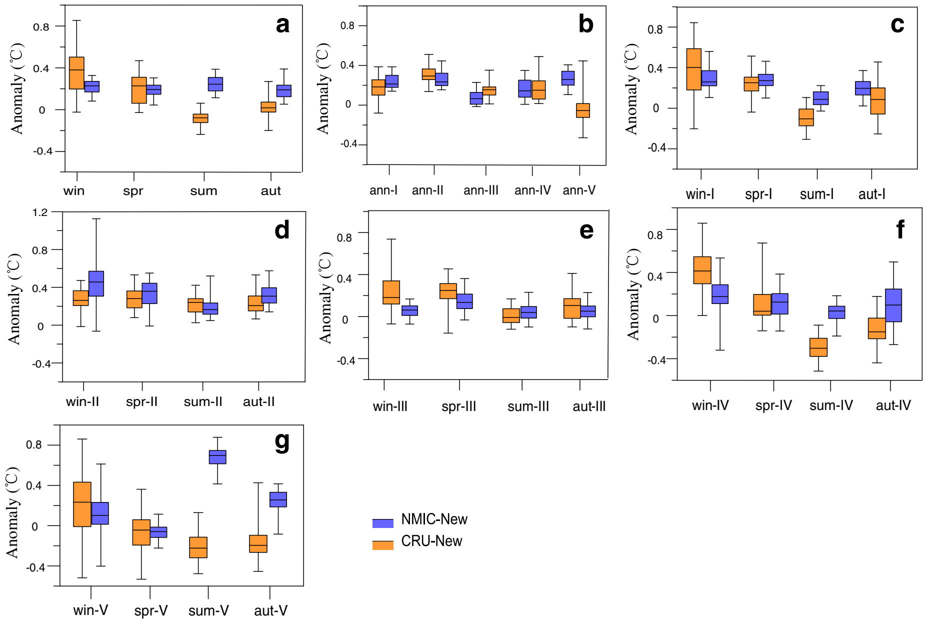

Fig. 5 The boxplots of annual and seasonal series difference in each geographical zone for the period of 1981–2007 (see Fig. 4). **a** - annual, China; **b** – annual, each zone; **c** – seasonal, zone I; **d** –seasonal, zone II; **e** – seasonal, zone III; **f** – seasonal, zone IV; **g** –seasonal, zone V

Figure 5 presents boxplots displaying temperature difference in each region for the period of 1981–2007. This period is from 1980s because the increasing of the differences occurs after 1980, which is related to a lot of urban constructed and the policy of Reform and Opening Up in China. The spacing between the different parts of the box helps indicate the degree of dispersion and skewness in the data. The bottom and top of the box are always the 25th and 75th percentile (the lower and upper quartiles, respectively), and the band near the middle of the box is always the 50th percentile (the median). Figure 5b is the boxplot of annual series difference from 1981–2007 for each zone and it shows that the difference for every zone appears to be that of the north (I, II, IV) greater than of the south (III). This is consistent with the UHI effect, which is more pronounced in the north than in the south (Wang et al. 1990; Hua et al. 2008; Zhang et al. 2010). The zone I in the northeast is the old industrial district developed rapidly after approximately mid-1970s, where the large cities began to be constructed meanwhile. The zone II in the mid-east is the political and cultural center of China, and here distribute some metropolises such as Beijing, Tianjin, and Shijiazhuang.

5.2.2 Seasonal trend

Seasonally, the common feature of temperature trend is that the temperature increases of our new series are lower than the NMIC and CRU series, which appear mainly after 1980 (see Fig. 2c–f). The NMIC summer series indicate a strong increasing trend, which is most related to the unusual high increasing trend of Qinghai-Tibet in summer (see Fig. 3p). Related references (Liu and Chen 2000; Yao et al. 2006) indicate lower warming rates compared to the NMIC data.

Figure 3 shows the gridding maps of three series based on four seasonal anomaly trends for the period 1951–2007. For four seasons, the increasing trends of our new series at most grids are lower than that of other series. The north part shows a larger difference than the South. The winter and spring differences are greater than that of summer and autumn. This agrees with the urbanization effect, which appears to be greater in the northern part and in winter compared to the southern part and other seasons (Wang et al. 1990; Ren et al. 2008; Hua et al. 2008; Zhang et al. 2010; Wang and Ge 2012). So the weighting of the urban impact in the New series results in a bigger difference between the New series and other series in winter and the northern part.

Figure 4 shows the seasonal temperature curves with each region for the three series. It can be seen that the linear trends of the three series in all figures are similar except for Qinghai-Tibet summer. Gradually after 1980, the temperature increasing trends of the new series (red) for all zones are almost lower compared to NMIC series (black) and CRU series (yellow). Figure 5a and c–g are the box plots to display seasonal series difference for the whole China and each region during 1981–2007. It shows that the temperature differences between CRU series and the new series for all zones are more significant in winter and spring than in summer and autumn. The seasonal differences between NMIC series and the new series are more significant in winter and spring for most zones except for the V zone (Qinghai-Tibet).

Concerning the temperature trend of Qinghai-Tibet zone during 1951–2007, there is still a divergence between different studies due to limited observation evidence and different average method of regional data. Especially for the early 1950s, the increasing trend given by NMIC is nearly 3 °C, which is much higher than the results from other studies (Liu and Chen 2000; Yao et al. 2006). We believe that the grid interpolation of station data in NMIC series may have magnified the influence of individual station data and accelerated the trend.

6 Conclusions and outlook

Using local station records to estimate large-scale climate warming is an important topic. The previous estimation using all stations without weighting usually exaggerated the regional warming trend. In this paper we re-estimated the mean warming trend of China during the last 60 years by considering the spatial scale of urban and using satellite observed land data. The homogenized meteorological observations are applied. The new estimate shows an increase over China by 1.28±0.12 °C. This new estimate of warming using land-weighted average is lower than that using un-weighted average (e.g. NMIC and CRU series). Spatially, the north part of China shows a larger difference than the south. Seasonally, the difference between the weighted trend and un-weighted trend is largest in winter. Temporally, the period after around 1980 shows a stronger difference, which is corresponding to the urbanization expansion and economic development speed in China. This difference in the warming trend (NMIC-New, CRU-New) between the un-weighted and weighted methods is large and accounts for 27 % (12 %) of the NMIC (CRU-China) un-weighted estimate on the total warming for the period of 1951–2007. Compared with rural warming trend from other studies, our estimate of 0.21 °C/decade for regional total warming is a litter higher than rural warming values (e.g. Zhang et al. (2010): 0.20 °C/decade of rural warming for China over 1961–2004; Jones et al. (2008): 0.15 °C/decade for eastern China over 1951–2004). The possible reasons for the differences include: (1) different methods (e.g. rural station series for Zhang et al. and Jones et al. versus all stations (urban and rural) in this study), and (2) different periods of analysis (1961–2004 for Zhang et al. (2010), 1951–2004 for Jones et al. (2008), and the longer period from 1951–2010 in this study). The differences in methods are potentially the more important.

The estimated regional warming trend shows the actual SAT change, which includes not only the natural climate change but also human activity impact, so both the greenhouse effect and the urbanization effect are kept in the regional temperature trend. This study implies that the weighting method of urban and rural records can reduce large-scale warming trend, so it is of importance to take into consideration the spatial scale of urban to better understand surface warming trend. The urban area is only a small part of earth land. The distance between the stations is usually greater than 50~100 km, but the influence of the city is often limited in a small circle with a radius of about 10 km or so (Wang and Ge 2012). Therefore, average temperatures for all stations without weighting will overestimate the urban impact. To study large-scale temperature change based on local ground station data, the spatial representation of urban needs to be considered.

Here, this study still includes uncorrected problems that could be addressed in future studies. For example, most stations in China are influenced by surrounding urbanization, and the remained rural stations are relatively rare. Therefore, the temperature data from the remained rural stations are difficult to represent rural temperature adequately at widely national scale. The rural area in China is relatively to all. In the future, this will be further addressed.

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References

Briffa KR, Jones PD (1993) Global surface air temperature variations over the twentieth century, Part 2: Implications for large-scale paleoclimatic studies of the Holocene. Holocene 3:77–88. doi:10.1177/095968369300300109

Brohan P, Kennedy JJ, Harris I et al (2006) Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850. J Geophys Res 111, D12106. doi:10.1029/2005JD006548

Easterling DR, Peterson TC (1995) A new method for detecting and adjusting for undocumented discontinuities in climatological time series. Int J Climatol 15:369–377. doi:10.1002/joc.3370150403

Folland CK, Rayner NA, Brown SJ et al (2001) Global temperature change and its uncertainties since 1861. Geophys Res Lett 28(13):2621–2624. doi:10.1029/2001GL012877, GL012877

Hansen J, Ruedy R, Sato M et al (2001) A closer look at United States and global surface temperature change. J Geophys Res 106:23947–23963. doi:10.1029/2001JD000354

Hansen J, Ruedy R, Sato M (2010) Global surface temperature change. Rev Geophys 48:RG4004. doi:10.1029/2010RG000345

Harris I, Jones PD, Osborn TJ et al (2013) Updated high-resolution grids of monthly climatic observations–the CRU TS3.10 data set. Int J Climatol, in press

Hausfather Z, Menne MJ, Williams CN et al (2013) Quantifying the effect of urbanization on U.S. historical climatology network temperature records. J Geophys Res. doi:10.1029/2012JD018509, in press

Hua LJ, Ma ZG, Guo WD (2008) The impact of urbanization on air temperature across China. Theor Appl Climatol 93:179–194. doi:10.1007/s00704-007-0339-8

Jones PD (1994) Hemispheric Surface air temperature variations: a reanalysis and an update to 1993. J Clim 7:1794–1802. doi:10.1175/1520-0442(1994)007

Jones PD, Raper SCB, Santer BD et al (1985) A grid point surface air temperature data set for the Northern Hemisphere. Tech. Rep. TR022, 251 pp., Carbon Dioxide Res. Div., U. S. Dep. of Energy, Washington, D. C. (Available at www.cru.uea.ac.uk/st/TR022.pdf.)

Jones PD, Osborn TJ, Briffa KR (1997) Estimating sampling errors in large-scale temperature averages. J Clim 10:2548–2568

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:10.1029/2008JD009616

Jones PD, Lister DH, Osborn TJ et al (2012) Hemispheric and large-scale land surface air temperature variations: an extensive revision and an update to 2010. J Geophys Res. doi:10.1029/2011JD017139

Li Q, Li W (2007) Development of the gridded historic temperature dataset over China during recent half century. Acta Met Sinica (in Chinese) 65:293–299

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. doi:10.1007/s00704-004-0065-4

Li Q, Zhang H, Chen J et al (2009) A mainland China homogenized historical temperature dataset of 1951–2004. Bull Am Meteorol Soc 90:1062–1065. doi:10.1175/2009BAMS2736.1

Liu XD, Chen BD (2000) Climatic warming in the Tibetan Plateau during recent decades. Int J Climat 20:1729–1742. doi:10.1002/1097-0088(20001130)20:14<1729::AID-JOC556>3.0.CO;2-Y

Liu J, Liu M, Deng X et al (2002) The land use and land cover change database and its relative studies in China. J Geogr Sci 12:275–282

Liu JY, Tian HQ, Liu ML (2005) China's changing landscape during the 1990s: large-scale land transformations estimated with satellite data. Geophys Res Lett 32, L02405. doi:10.1029/2004GL021649

Meko DM, Graybill DA (1995) Tree-ring reconstruction of Upper Gila River discharge. Water Resources Bulletin 31:605–616

Peterson TC, Easterling DR (1994) Creation of homogeneous composite climatological references series. Int J Climat 14:671–679. doi:10.1002/joc.3370140606

Peterson TC, Owen TW (2005) Urban heat island assessment: metadata are important. J Clim 18:2637–2646

Peterson TC, Karl TR, Jamason PF et al (1998) The first difference method: Maximizing station density for the calculation of long-term global temperature change. J Geophys Res 103:25967–25974

Quayle RG, Peterson TC, Basist AN et al (1999) An operational near-real-time global temperature index. Geophys Res Lett 26:333–335. doi:10.1029/1998GL900297

Ren YY, Ren GY (2011) A remote-sensing method of selecting reference stations for evaluating urbanization effect on surface air temperature trends. J Clim 24(7):3179–3189. doi:10.1175/2010JCLI3658.1

Ren GY, Zhou YQ, Chu ZY et al (2008) Urbanization effect on observed surface air temperature trend in North China. J Clim 21:1333–1348. doi:10.1175/2007JCLI1348.1

Smith TM, Ropelewski CF, Reynolds RW (1994) Optimal averaging of seasonal sea surface temperatures and associated confidence intervals (1860–1989). J Climate 7:949–964. doi:10.1175/1520-0442(1994)007<0949:OAOSSS>2.0.CO;2

Smith TM, Reynolds RW, Peterson TC et al (2008) Improvements to NOAA's historical merged land-ocean surface temperature analysis (1880–2006). J Clim 21:2283–2293. doi:10.1175/2007JCLI2100.1

Tang GL, Ding YH (2007) Impacts of the average air temperature derived from maximum and minimum temperatures on annual mean air temperatures series of China. J Appl Meteorol 2:187–192

Vogelmann JE, Helder D, Morfitt R et al (2001) Effects of Landsat 5 Thematic Mapper and Landsat 7 Enhanced Thematic Mapper Plus radiometric and geometric calibrations and corrections on landscape characterization. Remote Sens Environ 78:55–70. doi:10.1016/S0034-4257(01)00249-8

Wang F, Ge QS (2012) Estimation of urbanization bias in observed surface temperature change in China from 1980 to 2009 using satellite land-use data. Chin Sci Bull 57(14):1708–1715. doi:10.1007/s11434-012-4999-0

Wang WC, Zeng Z, Karl TR (1990) Urban heat islands in China. Geophys Res Lett 17:2377–2380. doi:10.1029/GL017i013p02377

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

Yao TD, Guo XJ, Thompson LG et al (2006) $\delta^{18}O$ record and temperature change over the past 100 years in ice cores on the Tibetan Plateau. Science in China (Ser. D) 49(1):1–9. doi:10.1007/s11430-004-5096-2

Zhang XG, Li XQ (1982) Some characteristics of temperature variation in China in the present century. Acta Met Sinica 2:198–208

Zhang AY, Ren GY, Zhou JX et al (2010) Urbanization effect on surface air temperature trends over China. Acta Meteorologica Sinica(in Chinese) 68(6):957–966

Zheng JY, Yin YH, Li BY (2010) A new scheme for climate regionalization in China. Acta Geographica Sinica 1:3–12

Zhou LM, Tucker CJ, Kaufmann RK et al (2001) Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999. J Geophys Res 106:20069–20083. doi:10.1029/2000JD000115