Environmental Research Letters

LETTER • OPEN ACCESS

Climatic warming in China during 1901–2015 based on an extended dataset of instrumental temperature records

To cite this article: Lijuan Cao *et al* 2017 *Environ. Res. Lett.* **12** 064005

Environmental Research Letters

OPEN ACCESS

RECEIVED
30 September 2016

REVISED
17 March 2017

ACCEPTED FOR PUBLICATION
24 March 2017

PUBLISHED
26 May 2017

LETTER

Climatic warming in China during 1901–2015 based on an extended dataset of instrumental temperature records

Lijuan Cao[1,6], Zhongwei Yan[2,6], Ping Zhao[3], Yani Zhu[1], Yu Yu[1], Guoli Tang[1] and Phil Jones[4,5]

1 National Meteorological Information Center, China Meteorological Administration, Beijing, 100081, People's Republic of China
2 Key Laboratory of Regional Climate-Environment for East Asia, Institute of Atmospheric Physics; University of Chinese Academy of Sciences, Beijing, 100029, People's Republic of China
3 Chinese Academy of Meteorological Sciences, Beijing 100081, People's Republic of China
4 Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ, United Kingdom
5 Center of Excellence for Climate Change Research, Department of Meteorology, King Abdulaziz University, Jeddah, 21589, Saudi Arabia
6 Authors to whom any correspondence should be addressed.

E-mail: caolj@cma.gov.cn **and** yzw@tea.ac.cn

Keywords: surface air temperature (SAT), long-term meteorological observations, homogenization, China, global warming

Supplementary material for this article is available online

Abstract

Monthly mean instrumental surface air temperature (SAT) observations back to the nineteenth century in China are synthesized from different sources via specific quality-control, interpolation, and homogenization. Compared with the first homogenized long-term SAT dataset for China by Cao *et al* (2013), which contained 18 stations mainly located in the middle and eastern part of China, the present dataset includes homogenized monthly SAT series at 32 stations, with an extended coverage especially towards western China. Missing values are interpolated by using observations at nearby stations, including those from neighboring countries. Cross validation shows that the mean bias error (MBE) is generally small and falls between 0.45 °C and −0.35 °C. Multiple homogenization methods and available metadata are applied to assess the consistency of the time series and to adjust inhomogeneity biases. The homogenized annual mean SAT series shows a range of trends between 1.1 °C and 4.0 °C/century in northeastern China, between 0.4 °C and 1.9 °C/century in southeastern China, and between 1.4 °C and 3.7 °C/century in western China to the west of 105 E (from the initial years of the stations to 2015). The unadjusted data include unusually warm records during the 1940s and hence tend to underestimate the warming trends at a number of stations. The mean SAT series for China based on the climate anomaly method shows a warming trend of 1.56 °C/century during 1901–2015, larger than those based on other currently available datasets.

1. Introduction

Climatic warming during the past century has been evident in worldwide surface air temperature (SAT) records (Hartmann *et al* 2013, Jones 2016). It is clear that long-term and homogeneous instrumental SAT series are essential for quantifying the observed climate trend. Great efforts have been made for decades to develop reliable long-term SAT series for different regions of the world (Jones *et al* 1999, Jones 2016).

The collection, compilation, and construction of long-term instrumental SAT data in China have also been on-going over recent decades (Tao *et al* 1991, Wang *et al* 1998, Cao *et al* 2013). However, the estimates of climatic warming trends during the last century for China in previous studies show a large range (from 0.3 °C–1.5 °C/century), primarily due to various data issues, especially for the early period before 1950 (Tang *et al* 2009). For comparison, the data of the regional mean SAT series based on a different number of stations for the period since the 1950s agree well with each other (e.g. Jones *et al* 2008). Cao *et al* (2013) established for the first time a set of homogenized long-term SAT series at 18 stations in middle and eastern China and showed a regional mean warming of 1.52 °C for the 1909–2010 period. Here, we update the data series and extend the

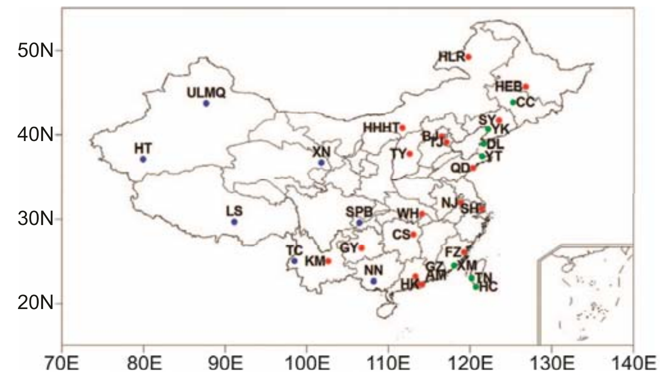

Figure 1. Distributions of 32 stations of long-term temperature series. (Red dots: the 18 stations in Cao *et al* (2013); green dots: new stations in the eastern part of China; blue dots: new stations in the western part of China.)

dataset towards western China in particular, where observations are sparse.

The extension to a more spatially complete dataset of long-term instrumental temperature observation series for China occurred mainly due to a number of pieces of early observation series becoming available for western China. At the same time, it is beneficial to update the existing dataset as five years have passed since the early work of Cao *et al* (2013) was undertaken (the final year then was 2010) and significant improvements have been made to the availability of SAT data in China in this period.

The present paper introduces how the new dataset 'China Homogenized Monthly Temperature Dataset (CHMTD-V1.0) during 1873–2015' is constructed, including quality-control, interpolation of missing records, and homogenization of the long-term series. The new dataset serves as an improved database for studying the geographical pattern of SAT change and, in particular, updating the estimate of the century-scale warming trend over China.

The rest of the paper is organized as follows. Section 2 introduces the sources of additional data and datasets used for comparison. Section 3 explains the basic data processing, including interpolation and homogenization techniques used to develop the dataset. Section 4 presents the results. Section 5 is a summary.

2. Data

The original SAT records and the associated metadata before 1951 are from two main sources. One is the early work 'Two climatic databases of long-term instrumental records of Chinese Academy of Sciences (CAS) in the People's Republic of China' (Tao *et al* 1991). The other is the long-term series of SAT and metadata developed since 2002 by the National Meteorological Information Center of the China Meteorological Administration (CMA), including digitized long-term instrumental records and metadata for the 60 largest cities of China. A further digitized long-term temperature dataset of 78 stations set up in 2013 is also included. The metadata, which are archived in text files for each station, include detailed information about changes in the observational instrumentation, times, locations and environment. The CMA also holds the original records of SAT and the associated metadata during 1951–2014 for over 2400 national meteorological stations across China (Cao *et al* 2016). Instrumental temperature records for Hong Kong and Macao are available from the websites of the Hong Kong Observatory and the Macao Meteorological and Geophysical Bureau, respectively. Instrumental temperature records for Tainan and Hengchun stations are available from the website of the Central Weather Bureau of Taiwan.

The CRUTEM4 (Jones *et al* 2012, Osborn and Jones 2014) database of SAT within the China area is used to compare the regional average series based on the climate anomaly method (CAM) (Jones 1994, Jones and Moberg 2003). CRUTEM4 additionally includes the previously published 18 homogenized temperature time series (Cao *et al* 2013). The GISTEMP dataset is also used for comparison, which does not include the present homogenized station series from China. A principle rule for choosing stations for the present dataset is that the station is within at least the 30 yr series of SAT records before 1951 if it is in eastern China, or over 10 yr if it is in western China (to the west of 110 E). As shown in figure 1, the 32 stations chosen are reasonably well distributed over China. Compared with the dataset of Cao *et al* (2013), the new dataset includes seven more stations in western China with a relatively long observation series. For eastern China, there are also seven new stations, including two from Taiwan. Table 1 shows the station names and their abbreviations for the 32 stations in figure 1.

3. Methods

3.1. Data quality control and interpolation

The original daily mean maximum and minimum temperature (Tmax and Tmin) series records of

Table 1. Station names and their abbreviations for the 32 stations in figure 1.

Station no.	Station name	Abbreviation	Station no.	Station name	Abbreviation
45005	Hongkong	HK	54857	Qingdao	QD
45011	Macao	AM	55591	Lhasa	LS
50527	Hailar	HLR	56739	Tengchong	TC
50953	Harbin	HEB	56778	Kunming	KM
51463	Wulumuqi	ULMQ	57494	Wuhan	WH
51828	Hetian	HT	57516	Shapingba	SPB
52866	Xining	XN	57679	Changsha	CS
53463	Hohehot	HHHT	57816	Guiyang	GY
53772	Taiyuan	TY	58238	Nanjing	NJ
54161	Changchun	CC	58367	Shanghai	SH
54342	Shenyang	SY	58847	Fuzhou	FZ
54471	Yingkou	YK	59134	Xiamen	XM
54511	Beijing	BJ	59287	Guangzhou	GZ
54527	Tianjin	TJ	59358	Tainan	TN
54662	Dalian	DL	59431	Nanning	NN
54765	Yantai	YT	59559	Hengchun	HC

Table 2. Missing percentages of records and the number of changepoints at 14 stations from their start dates to the end of 2015.

Station no.	Station name	Start time (month/year)	Length (months)	Missing months	Missing percentage (%)	Number of changepoints	
						Before 1950	After 1951
51463	Wulumuqi	01/1930	1032	113	10.95	0	2
51828	Hetian	01/1942	888	32	3.60	0	0
52866	Xining	11/1936	950	11	1.16	0	3
54161	Changchun	01/1909	1284	56	4.36	1	0
54471	Yingkou	01/1905	1332	74	5.56	0	0
54662	Dalian	01/1905	1332	78	5.86	1	0
54765	Yantai	01/1905	1332	73	5.48	0	1
55591	Lhasa	05/1935	968	72	7.44	0	2
56739	Tengchong	01/1916	1200	112	9.33	0	1
57516	Shapingba	01/1924	1104	4	0.36	0	1
59358	Tainan	01/1897	1428	0	0.00	0	0
59134	Xiamen	01/1915	1212	56	4.62	0	2
59431	Nanning	01/1922	1128	57	5.05	0	2
59559	Hengchun	01/1897	1428	0	0.00	0	1

1951–2015 were collected from the China National Stations' Fundamental Elements Datasets V3.0 (Ren *et al* 2012). These datasets are quality-controlled and updated every month and serve as the latest version of the surface climate datasets with the best quality and integrity among those having been applied to date (Ren *et al* 2012).

We perform compilation and quality control using the method of Cao *et al* (2013) to determine the reliability of each station's monthly SAT series and then consider any obviously erroneous value as a missing value. Table 2 shows the percentage of missing records for the 14 new stations of the long-term monthly mean SAT series. Only two stations, Tainan and Hengchun in Taiwan, have a continuous monthly mean SAT from their start dates to the end of 2015. Ten stations have missing rates between 0.36% and 7.44%. Wulumuqi and Tengchong have the largest missing rates (10.95% and 9.33%, respectively). Hetian station started in 1942, and has the shortest time series among all 32 stations. It is beneficial to interpolate some missing records, especially for the western part of China. To do so, records at neighboring stations (including some in neighboring countries) with instrumental observations before 1950, particularly during the 1940s, were used. After infilling all those missing records, we produced a complete temperature series for all the stations.

When undertaking the interpolation for a given station, the reference stations were chosen from those of 152 stations in the China area (figure 2, green dot), which are within a distance of 300 km from the candidate station and have data value for more than 10 yr before 1951. It is difficult for the seven stations in western China to choose neighboring temperature series as none may exist within China. We therefore chose 76 stations bordering China to interpolate missing records at the stations in western China. These stations are located in 11 countries: Bangladesh, India, Kyrgyzstan, Kazakhstan, Laos,

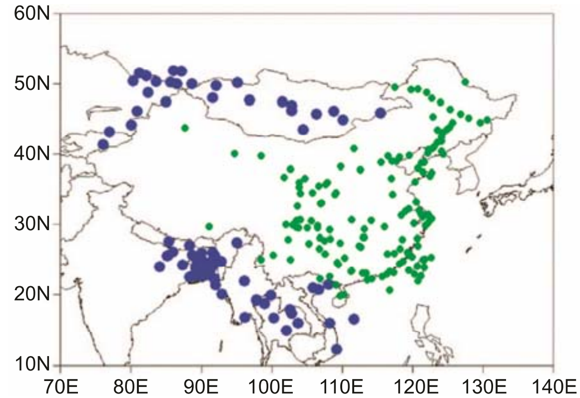

Figure 2. Location of 76 stations (blue) around China and 152 stations (green) in China for interpolation.

Mongolia, Myanmar, Russia, Thailand, Vietnam and Nepal (figure 2, blue dot). The temperature data series at the stations outside China are from CMA's first global monthly temperature dataset over land, which was developed by integrating four existing global temperature datasets and several regional datasets from major countries or regions (Xu *et al* 2014). The temperature series of Kathmandu extending from January 1921 to December 1975 is archived at CRU (via P D Jones). To ensure that the temperature series at the reference stations are highly correlated with those at the candidate station, we set a distance threshold of 500 km. For Wulumuqi, Hetian and Lhasa stations, the threshold distance was enlarged to 1000 km.

A three-step interpolation technique for the monthly mean SAT anomaly from the local climatological mean is applied, using one of four independent statistical approaches for each step, i.e. the standardized method, partial least squares regression, multivariate linear regression and gradient plus inverse distance square method (full details given in Cao *et al* 2013). Cross validation is conducted to assess the reliability of the interpolation results. Table 3 shows the mean bias error (MBE) and root mean square error (RMSE) for each of the 12 stations from the first year of the station observations to 2015.

As table 3 shows, MBE is generally small and falls between 0.45 °C and −0.35 °C. RMSE is smaller than 1 °C at six stations (Xining, Yingkou, Dalian, Yantai, Xiamen, and Nanning) and is generally below 1 °C at Changchun and Lhasa. These interpolation errors are similar in magnitude to previous results for stations in eastern China (Cao *et al* 2013). A relatively large RMSE (between 1.5 °C and 1.6 °C) is found at two stations in western China (Wulumuqi, Lhasa) for 119 months of interpolated values.

In total, we interpolated 738 monthly values for 12 stations (accounting for 5.4% of the total monthly records) to develop a continuous time series of monthly mean SAT from the start year up to 2015 for the 32 stations.

3.2. Homogenization of SAT time series

The inhomogeneity of a SAT time series is usually expressed as a sudden change (breakpoint) compared with neighboring station records. A homogeneous time series should diminish the sudden changes due to non-climatic factors, such as changes in observational locations, times and instruments. A variety of homogenization algorithms have been developed and assessed in recent years (Venema *et al* 2012). In this work, we applied some existing homogenization methods together with station metadata to perform the inhomogeneity detection and adjustment. Any gradual trend biases, e.g. due to an enhancing urban heat island effect during recent decades, may remain in the homogenized series for some studied sites.

The RHtests version 3 software package (Wang and Feng 2010) was used as the primary method to detect and adjust changepoints. This package includes the PMTred algorithm, which is based on the penalized maximum *t* (PMT) test, and the PMFred algorithm, which is based on the penalized maximum *F* (PMF) test (Wang 2008). The PMT test is a relative homogeneity test and must be used with a reference series. The PMF test can be used without a reference series. Cao and Yan (2012) showed that the PMTred algorithm is suitable for detecting multiple changepoints with a reference series representing a regional temperature series when the observational network is dense, while the PMFred algorithm is often applied to a sparse observational network where a reference series may be quite distant. Therefore, we use both PMFred and PMTred algorithms with a statistical test at the 1% significance level.

Firstly, for the time series of monthly mean SAT at the 14 new stations before 1950, we apply the PMFred algorithm without a reference series because the observational stations were sparse during this period. To increase the reliability of the PMFred method in detecting changepoints, we repeat the above work using the two-phase regression method (Easterling and Peterson 1995) and a running student's *t*-test. When one changepoint is detected by at least two methods or is supported by the metadata, it is accepted as a break

Table 3. Error estimation of cross validation of interpolation methods at 12 stations from their starting observations to 2015 (MBE: mean bias error, RMSE: root mean square error).

Station no.	Station name	Missing time of record (month/year)	Missing months in record	Interpolation method	Error MBE (°C)	Error RMSE (°C)
51463	Wulumuqi	06/1931-05/1933 09/1933-12/1940 11/1945	113	Relaxed integrated method	−0.21	1.606
51828	Hetian	08/1944 02/1945-07/1945 01/1951-01/1953	32	Relaxed integrated method	0.36	1.469
52866	Xining	09/1943-02/1944 01/1945-04/1945 09/1949	11	Integrated method	−0.04	0.613
54161	Changchun	05/1941 05/1942-12/1942 08/1943, 12/1943 01/1944-12/1945 01/1947 05/1948-12/1948	44	Integrated method	−0.08	0.644
		01/1946-12/1946	12	Relaxed integrated method	0.08	1.211
54471	Yingkou	03/1943-12/1945 01/1947-04/1949	62	Integrated method	−0.00	0.432
		01/1946-12/1946	12	Gradient plus inverse distance square	0.26	0.588
54662	Dalian	12/1943 07/1948-09/1948 01/1949-05/1950	21	Integrated method	0.35	0.484
		01/1944-06/1948 10/1948-12/1948	57	Gradient plus inverse distance square	−0.35	0.642
54765	Yantai	11/1941 01/1944-06/1948 10/1948-03/1950	73	Integrated method	0.41	0.542
55591	Lhasa	01/1938-12/1940 07/1949-10/1951 07/1952-12/1952	66	Relaxed integrated method	−0.27	0.986
		03/1959 06/1968-10/1968	6	Integrated method	0.3	1.5
56739	Tengchong	07/1940 11/1940 10/1941 12/1941-12/1950	112	Integrated method	−0.11	1.17
57516	Shapingba	09/1938-12/1938	4	Integrated method	−0.06	1.187
59134	Xiamen	12/1915-12/1916 05/1923-12/1923 01/1943-02/1943 08/1943-12/1943 08/1944-11/1946	56	Integrated method	0.45	0.563
59431	Nanning	08/1930-03/1931 11/1939-10/1941 11/1943-12/1943 09/1944-12/1944 11/1949-05/1950	45	Integrated method	−0.01	0.658
		01/1945-12/1945	12	Gradient plus inverse distance square	0.25	0.597

point. When the changepoints detected by different methods are close to each other (within two years), these changepoints are considered as one and its occurrence time is determined by available metadata or is set to the first occurring year if without metadata.

Secondly, for the 12 stations (excluding Tainan and Hengchun) during 1951–2015, the PMTred algorithm considering a reference series is applied to detect changepoints. Each reference series is constructed on the basis of stations with continuous and homogeneous

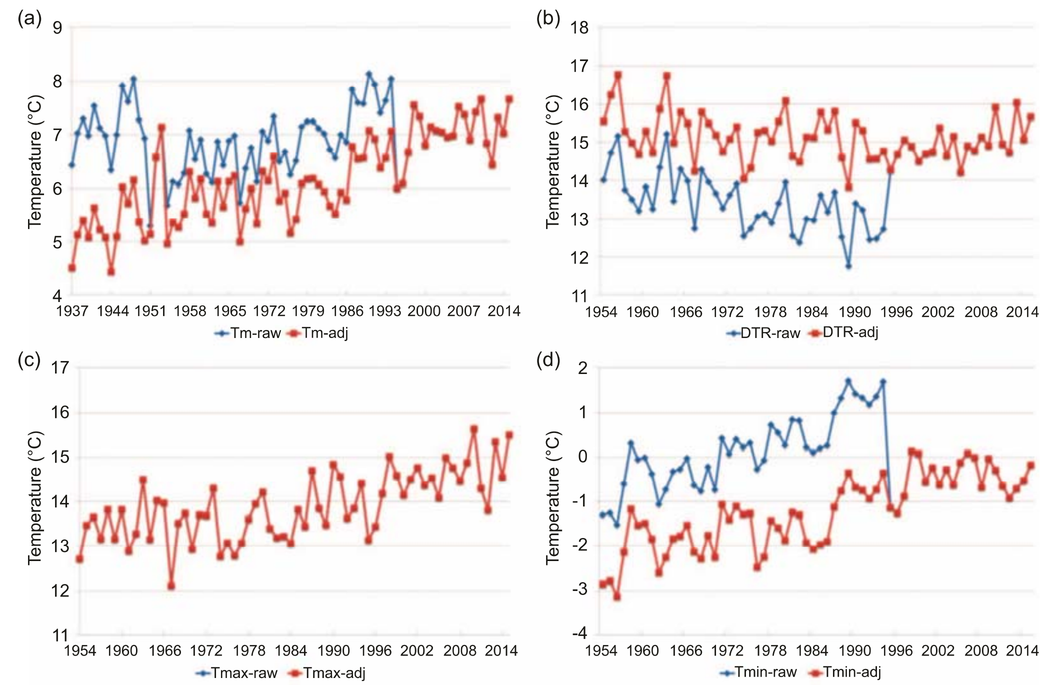

Figure 3. (*a*) Original (RAW) and adjusted (ADJ) Tm series from 1937–2015 for Xining station; (*b*) original (RAW) and adjusted (ADJ) DTR series from 1954–2015; (*c*) same as (*b*) but for Tmax series (no changepoints detected); (*d*) same as (*b*) but for Tmin series.

series (hereafter the reference stations). The reference stations are selected from the national network of 2419 meteorological stations across China (Cao *et al* 2016). The homogeneity of the time series at each reference station is checked by using the PMFred algorithm. The reference series is chosen to highly correlate with the tested station (with a correlation coefficient larger than 0.8). For each tested station, if there are more than two reference stations, their arithmetic average is defined as a reference series.

In the third step, possible changepoints in the 1950s are further detected by using the PMFred algorithm to ensure the continuity of the whole series. In fact, the metadata shows that many stations were relocated in the years during the early 1950s when the national meteorological network was rebuilt.

Table 2 shows the detected changepoints at the 14 new stations. There are no breakpoints at three stations (Hetian, Yingkou and Tainan). Each temperature series identified to contain significant changepoints is then adjusted to the latest segment of the data series using the mean-adjustments of RHtestsV3. Finally, we obtain the homogenized time series of monthly mean SAT at each of the 14 stations. Figure 3 shows the time series of the annual mean SAT anomaly at Xining station from 1937–2015 as an example. It is notable that discontinuity dates are different for the Tmax and Tmin series (figures 3(*b*)−(*d*)). In Tmin, there are two changepoints detected due to relocation in 1975 and 1995, while the Tmax series is homogeneous. This means the two relocations had little influence on the Tmax series. This phenomenon is quite common for temperature observations in China. Overall, the Tmin series have more changepoints than the Tmax series, implying that the Tmin measurement is more sensitive to changes in the observation system in China. A physical reason for is that the Tmin series usually has a smaller variance than Tmax is in this region, hence any non-natural biases in the Tmin series are more statistically significant.

When averaging Tmax and Tmin to generate the Tm series, the discontinuity still exists. The long-term series of Tm has one more changepoint in 1951 (figure 3(*a*)), corresponding to a relocation recorded in the metadata. Xining station was moved in January 1951 from downtown to the nearby airport, which was located in the eastern suburb, about 8 km away from the downtown location, causing the jump in the temperature series (figure 3(*a*)). The adjusted Tm series shows an increasing trend.

4. Cases of relative warmth during the 1940s

It is clear that the century-scale warming trend estimation is uncertain when using different datasets (Tang *et al* 2009, Jones 2016). The most significant differences occurred during the 1920s–1940s. In particular during the 1940s, China experienced wars and so a large number of observations are missing. Figure 4 gives the temperature series for Beijing and Nanjing stations during 1905–2015 before and after homogenization. For Beijing station, we can hardly see a warming trend in the raw temperature series before

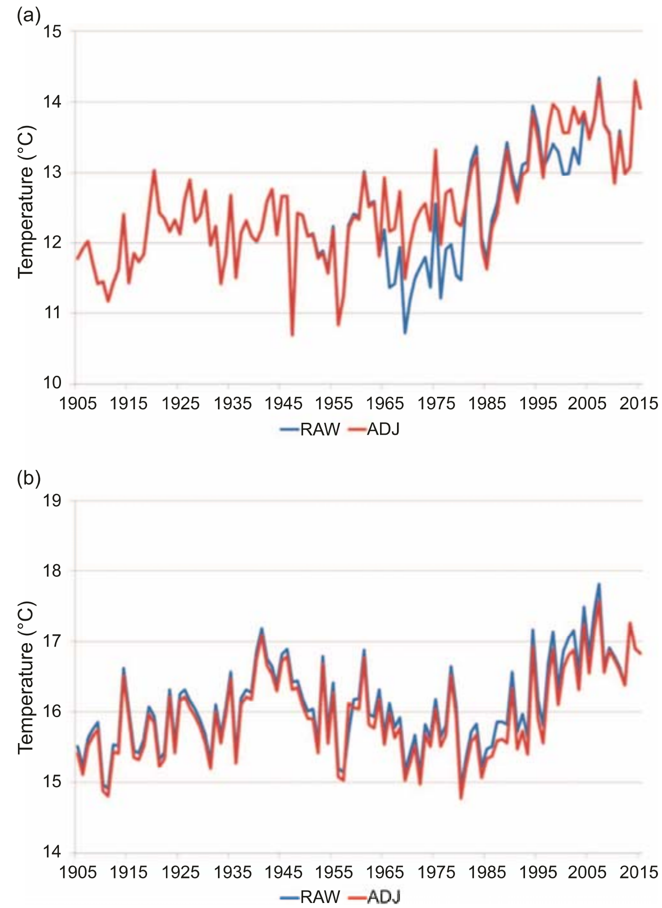

Figure 4. Time series of original (RAW) and adjusted (ADJ) Tm series of (*a*) Beijing and (*b*) Nanjing stations during 1905–2015.

1965, when the station was moved from downtown to the Southeast of Daxing District about 3.88 km away. The homogenized series (the red line) shows a consistent warming trend and the relative warmth before the 1940s is not as obvious as in the raw data. Based on the present method, the Beijing series did not exhibit significant changepoints before 1951, though it was possible to make some minor adjustments based on other methods (e.g. Yan *et al* 2001).

For Nanjing station, a warm peak occurs around 1941. However, Nanjing had many continuous missing months during 1938–1945. The early warm peak was a result of interpolation from three stations (Shanghai, Xuzhou and Dafeng) (Cao *et al* 2013). According to the metadata, Nanjing station was located in the urban district during the 1940s and observations were missed due to the war. In 1958, the station was moved to the Yuhua suburb to the south and southeast of the downtown location (6.8 km away), with a declining jump of the temperature records (albeit it is not statistically detectable).

By analyzing the metadata, we found that in China many stations (about 40% of the studied stations in this paper) moved from the city center to a suburb due to the rapid urbanization development shortly after the foundation of the People's Republic of China in 1949. The environment of the stations did not accord with the observation criteria in the earlier periods and these relocations usually led to obvious jumps to cooler temperatures. Figure 3(*a*) shows a typical case (see the change point around 1951). Thus, cases such as Nanjing station need more attention and perhaps further adjustments. In general, there is still potential for further homogenization of the present dataset because the present work has adjusted only the most significant biases in the station series.

5. Century-scale warming trends in China

Figure 5 shows that eight stations had records from 1901 or earlier. After 1901, the number of stations with records increased rapidly, reaching 18 stations in 1909 and 32 stations in 1942. Therefore, we focus on analyzing the trend of temperature change for China during 1901–2015. Linear trends are calculated for the annual mean SAT series by using the least-squares regression method, with significance assessment based on the *t*-test ($\alpha = 0.05$).

Figure 6 shows the linear trends of the annual mean SAT series for the 32 stations from 1901 or the later start year to 2015, compared with the results

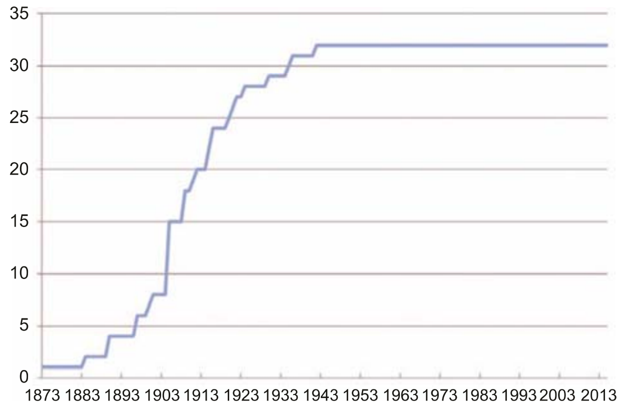

Figure 5. Number of stations during 1873–2015.

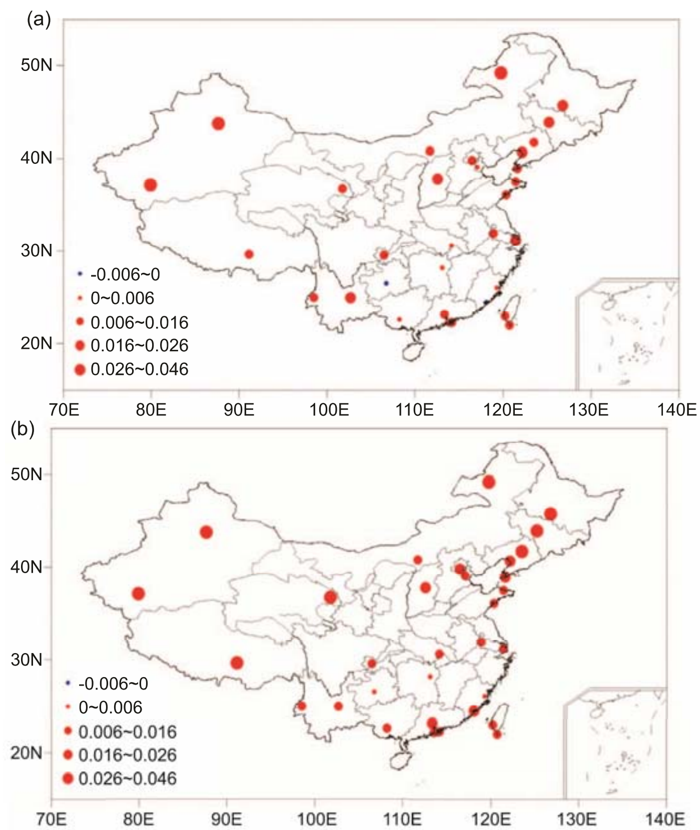

Figure 6. (*a*) Linear trend (°C/year) of unadjusted annual mean SAT at Hong Kong, Macao, Beijing, Tianjin, Qingdao, Shanghai, Tainan and Hengchun stations from 1901–2015 and the other 24 stations from the start of the observation to 2015; (*b*) same as figure 6 (*a*) but for the adjusted data.

based on the unadjusted station data over the 32 stations. As figure 6(*a*) shows, based on the unadjusted SAT series, nine stations have large warming trends over 1.5 °C/century, with the largest warming rates over 3.0 °C/century at three stations in the northeast (Hailar) and northwest (Wulumuqi, and Hetian). Eight stations mostly located in southern China (Macao, Tianjin, Wuhan, Shapingba, Changsha, Fuzhou, Xiamen and Nanning) have a range of small trends between −0.6 °C and 0.4 °C/century. The other 15 stations have a range of trends between 0.5 °C and 1.5 °C/century.

In figure 6(*b*), the homogenized annual mean SAT series show larger warming trends in general. The largest warming trends occur at Harbin (4.0 °C/century), Wulumuqi (3.7 °C/century), and Changchun (3.5 °C/century), which are located in the most northeast or northwest of China. By and large, the original time series tend to underestimate the local warming trends during the overall period from

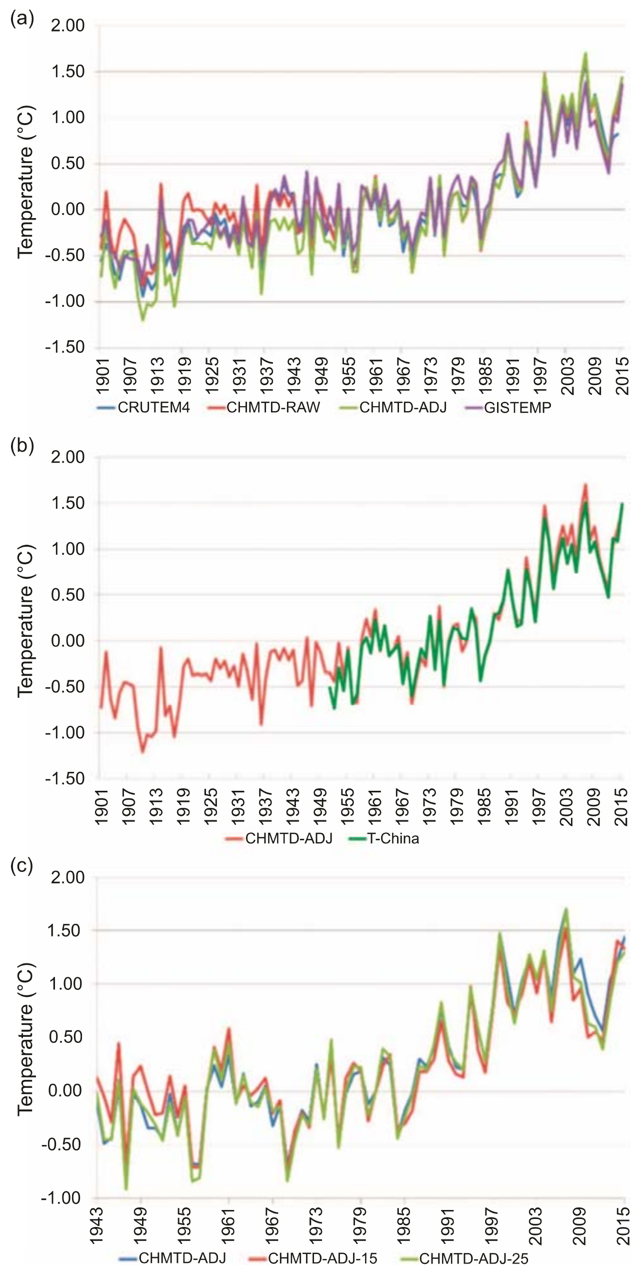

Figure 7. (*a*) The mean temperature anomaly series for China during 1901–2015 based on the original (CHMTD-RAW) and adjusted (CHMTD -ADJ) station data, compared with those based on CRUTEM4 and GISTEMP. The anomalies (°C) are from the 1961–1990 climatology. (*b*) The CHMTD–ADJ series (1901–2015) versus the T-China series (1951–2015) based on 2419 stations (Cao *et al* 2016). (*c*) The mean temperature anomaly series for China during 1943–2015. CHMTD-ADJ involves all the 32 stations; CHMTD-ADJ-25 involves the 25 stations with continuous records since 1920 or earlier; CHMTD-ADJ-15 involves the 15 stations with continuous records since 1905 or earlier.

1901–2015. Similar results were noted in previous studies. Li and Yan (2009) showed that many stations in China moved from some urbanized locations to an out-of-town location during their history, causing cooling biases in the SAT series. Comparatively, the adjusted data present a more geographically coherent pattern of climatic warming (figure 6(*b*)) than the original data do (figure 6(*a*)). The adjusted data demonstrate a range of trends between 1.1 °C and 4.0 °C/century in northern China, between 0.4 °C and 1.9 °C/century in southeastern China, and between 1.4 °C and 3.7 °C/century in western China (to the west of 110 E).

To calculate the country-wide average trend, we applied the most widely used method, CAM (Jones 1994, Jones and Moberg 2003), to avoid the biases caused by uneven station density. The base period from 1961–1990 was taken to calculate the mean climatology and temperature anomalies. Grid-box anomaly values were then produced by averaging the individual station anomaly values within each 5° × 5° grid box. Figure 7 shows the time series of SAT anomalies for China during 1901–2015 based on the original and adjusted data. The data from CRUTEM4 and GISTEMP are also used for comparison.

As figure 7(*a*) shows, the four temperature series of CRUTEM4, GISTEMP, original (CHMTD-RAW) and adjusted (CHMTD -ADJ) station data are similar to each other from the 1950s. The correlation coefficients among them are beyond 0.99 for the period since 1951. The regional mean SAT series for China based on the 32 stations agrees well with that based on a much denser station network for the period 1951–2015 (T-China in figure 7(*b*)). The T-China series is the average of 2419 stations' homogenized Tm series over the whole of China (Cao *et al* 2016). The long-term temperature series have slight trends before the late 1960s, followed by a rapid warming after about 1970. For the period 1901–2015, the linear trend is 1.13 °C ± 0.21 °C/century based on the original data, 1.56 °C ± 0.20 °C/century based on the homogenized data, and 1.21 ± 0.16 and 1.30 °C ± 0.19 °C/century based on GISTEMP and CRUTEM4, respectively.

The warming trend estimated from the adjusted data is larger than that based on the raw data because, in many cases, the raw station data involve cooling biases as discussed *supra*. Note that CRUTEM4 additionally includes 18 stations of the homogenized dataset published in Cao *et al* (2013), thus showing a trend nearest to that based on the present adjusted data. GISTEMP does not include the present homogenized data but with some processing of homogenization of the original data used, hence the trend based on GISTEMP is between that of the raw data and that of CRUTEM4. It is also worthwhile noting that the difference between different datasets in terms of the regional mean series appears smaller than those between the raw and adjusted data for individual stations because inhomogeneities at individual stations may compensate each other when calculating the regional mean.

Uncertainty in the regional mean series also arises from the different number of stations during the different periods. Two series for the period 1943–2015 are present in figure 7(*c*) in addition to the original China mean temperature anomaly series involving 32 stations. One involves 25 stations with continuous records since 1920 or earlier; the second involves 15 stations with continuous records since 1905 or earlier. The differences among the three series during 1943–2015, as shown in figure 7(*c*), are acceptable and serve as measures of possible uncertainties in the early parts of the long-term series.

According to figure 7, the warmest year for China during the period of study is 2007, with the SAT anomaly being 1.69 °C/1.70 °C based on the original/adjusted data. Following the relatively cool years of 2010–2012, the SAT anomalies tend to recover in 2013–2015.

6. Summary

Via consistent quality control, multi-way interpolation and homogenization in this study, we have established an extended set of monthly mean SAT series in China back to the 19th century. The dataset includes 32 stations across China and is available at http://data.cma.cn/ according to the data sharing policy of the CMA. Different source datasets are synthesized to produce the new dataset. Compared to the earlier version dataset of Cao *et al* (2013), the new dataset has a much improved coverage towards western China, with nine stations located to the west of 110 E.

Several homogenization methods and available metadata were applied. Major inhomogeneous biases in the original data were adjusted. Compared to the original data, the adjusted series of annual mean SAT shows a larger warming trend for most stations. The warming rates range from 1.1 °C–4.0 °C/century in northern China. Trends are generally weaker in southeastern China.

The regional mean SAT series for China based on the 32 stations agrees well with that based on a much denser station network for the period 1951–2015. The linear trend in the regional mean SAT series of 1901–2015 is 1.56 °C ± 0.20 °C/century, with an enhanced warming rate of 0.26 °C ± 0.04 °C/decade for the recent period 1951–2015. There was little trend over the early period before 1951 due to relative warmth around the 1920s in the region (Zeng *et al* 2003). Uncertainty mainly arises from the sparse observations during the early period. There is potential to further homogenize the early series before 1950.

Acknowledgments

This study was supported by the CAS project (XDA05090000) and MOST (2016YFA0600400). LJC is also supported by the Youth Talent Plan of China Meteorological Administration. PDJ has been supported by the US Department of Energy (Grant DE-SC0005689).

References

Cao L J and Yan Z W 2012 Progress in research on homogenization of climate data *Adv. Clim. Change Res.* **3** 59–67

Cao L J, Zhao P, Yan Z W, Jones P D, Zhu Y N, Yu Y and Tang G L 2013 Instrumental temperature series in eastern and central China back to the nineteenth century *J. Geophys. Res. Atmos.* **118** 8197–209

Cao L J, Zhu Y N, Tang G L, Yuan F and Yan Z W 2016 Climatic warming in China according to a homogenized dataset from 2419 stations *Int. J. Climatol.* **36** 4384–92

Easterling D R and Peterson T C 1995 A new method for detecting and adjusting for undocumented discontinuities in climatological time series *Int. J. Climatol.* **15** 369–77

Hartmann D L *et al* 2013 Observations: atmosphere and surface *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed T F Stocker *et al* (Cambridge: Cambridge University Press) pp 159–254

Jones P D, Lister D H and Li Q 2008 Urbanization effects in large-scale temperature records, with an emphasis on China *J. Geophys. Res.* **113** D16122

Jones P D 1994 Hemispheric surface air temperature variations: a reanalysis and an update to 1993 *J. Clim.* **7** 1794–802

Jones P D and Moberg A 2003 Hemispheric and large-scale surface air temperature variations: an extensive revision and an update to 2001 *J. Clim.* **16** 206–23

Jones P D, New M, Parker D E, Martin S and Rigor L G 1999 Surface air temperature and its changes over the past 150 yr *Rev. Geophys.* **37** 173–99

Jones P D 2016 The reliability of global and hemispheric surface temperature records *Adv. Atmos. Sci.* **33** 269–82

Jones P D, Lister D H, Osborn T J, Harpham C, Salmon M and Morice C P 2012 Hemispheric and large scale land surface air temperature variations: an extensive revision and an update to 2010 *J. Geophys. Res.* **117** D05127

Li Z and Yan Z W 2009 Homogenized daily mean/maximum/minimum temperature series for China from 1960–2008 *Atmos. Oceanic Sci. Lett.* **2** 236–42

Osborn T J and Jones P D 2014 The CRUTEM4 land-surface air temperature data set: construction, previous versions and dissemination via Google Earth *Earth Syst. Sci. Data* **6** 61–8

Ren Z H, Yu Y, Zou F L and Xu Y 2012 Quality detection of surface historical basic meteorological data *J. Appl. Meteorol. Sci.* **23** 739–47 (in Chinese)

Tang G L, Ding Y H, Wang S W, Ren G Y, Liu H B and Zhang L 2009 Comparative analysis of the time series of surface air temperature over China for the last 100 yr *Adv. Clim. Change Res.* **5** 71–8 (in Chinese)

Tao S, Fu C, Zeng Z, Zhang Q and Kaiser D 1991 Two long-term instrumental climatic data bases of the People's Republic of China ORNL:CDIAC-47 (Oak Ridge, TN: Oak Ridge National Laboratory)

Venema V K C *et al* 2012 Climate of the past benchmarking homogenization algorithms for monthly data *Clim. Past* **8** 89–115

Wang X L and Feng Y 2010 *RHtestsV3 User Manual* Climate Research Division, Atmospheric Science and Technology Directorate, Science and Technology Branch, Environment Canada pp 28

Wang S W, Ye J L, Gong D Y, Zhu J H and Yao T D 1998 Construction of mean annual temperature series for the last one hundred years in China *Q. J. Appl. Meteorol.* **9** 392–401 (in Chinese)

Wang X L 2008 Accounting for autocorrelation in detecting mean shifts in climate data 493 series using the penalized maximal t or F test *J. Appl. Meteor. Climatol.* **47** 2423–44

Xu W H, Li Q X, Yang S and Xu Y 2014 Overview of global monthly surface temperature data in the past century and preliminary integration *Adv. Clim. Change Res.* **5** 111–17

Yan Z W, Yang C and Jones P D 2001 Influence of inhomogeneity on the estimation of mean and extreme temperature trends in Beijing and Shanghai *Adv. Atmos. Sci.* **18** 309–22

Zeng Z M, Yan Z W and Ye D Z 2003 Comparing two global warming events in the 20th century *Clim. Environ. Res.* **8** 319–30 (in Chinese)