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• **Data Description Article** •

Further-Adjusted Long-Term Temperature Series in China Based on MASH

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ABSTRACT

A set of homogenized monthly mean surface air temperature (SAT) series at 32 stations in China back to the 19th century had previously been developed based on the RHtest method by Cao et al., but some inhomogeneities remained in the dataset. The present study produces a further-adjusted and updated dataset based on the Multiple Analysis of Series for Homogenization (MASH) method. The MASH procedure detects 33 monthly temperature records as erroneous outliers and 152 meaningful break points in the monthly SAT series since 1924 at 28 stations. The inhomogeneous parts are then adjusted relative to the latest homogeneous part of the series. The new data show significant warming trends during 1924–2016 at all the stations, ranging from 0.48 to 3.57°C (100 yr)$^{-1}$, with a regional mean trend of 1.65°C (100 yr)$^{-1}$; whereas, the previous results ranged from a slight cooling at two stations to considerable warming, up to 4.5°C (100 yr)$^{-1}$. It is suggested that the further-adjusted data are a better representation of the large-scale pattern of climate change in the region for the past century. The new data are available online at http://www.dx.doi.org/10.11922/sciencedb.516.

Key words: homogenization, Multiple Analysis of series for homogenization (MASH), monthly temperature series, long-term trend, China

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1. Introduction

Homogeneous long-term surface air temperature (SAT) observations are essential for assessing and attributing global and regional climate change. However, inhomogeneity is difficult to avoid because of non-natural changes such as those at the observing location, the environment, instruments, and algorithms for calculating any particular climate variable (Yan

Dataset Profile

Dataset title	Further-adjusted long-term temperature series in China
Time range	Monthly surface air temperature from the start of observation to December 2016
Geographical scope	China
Data format	".txt"
Data volume	386 KB for the monthly temperature series; 1 KB for the station information
Data service system	http://www.sciencedb.cn/dataSet/handle/516. DOI: 10.11922/sciencedb.516
Sources of Funding	Chinese Academy of Sciences International Collaboration Program (Grant No. 134111KYSB20160010); National Natural Science Foundation of China (Grant Nos. 41505071 and 41475078); UK–China Research & Innovation Partnership Fund through the Met Office Climate Science for Service Partnership (CSSP) China as part of the Newton Fund
Dataset composition	The dataset contains a station information file named "station information.txt", and 12 monthly SAT files named "M01H.txt", "M02H.txt", "M03H.txt", "M04H.txt", "M05H.txt", "M06H.txt", "M07H.txt", "M08H.txt", "M09H.txt", "M10H.txt", "M11H.txt" and "M12H.txt"

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et al., 2014). The inhomogeneities in a climate series affect the estimation of not only the mean climate trend but also those of climate extremes in different ways (Trewin and Trevitt, 1996; Li et al., 2014). Over the past decades, homogenized local observations have increasingly been applied in global SAT datasets, such as those of the Global Historical Climatology Network (Vose et al., 1992; Peterson and Vose, 1997; Lawrimore et al., 2011) and the Climatic Research Unit (Jones, 1994; Jones and Moberg, 2003; Brohan et al., 2006; Jones et al., 2012). A new integrated and homogenized global monthly land surface air temperature dataset for the period since 1900 was recently developed (Xu et al., 2017).

The collection, compilation and processing of long-term instrumental SAT observations in China have also been ongoing over the past few decades (Tao et al., 1991; Cao et al., 2013). A number of century-scale SAT series for China have been constructed (Zhang and Li, 1982; Wang, 1990; Tang and Lin, 1992; Lin et al., 1995; Wang et al., 1998; Tang and Ren, 2005; Tang et al., 2009; Li et al., 2010). Li et al. (2017) assessed the existing long-term SAT series for China compared with the historical climate simulations of the CMIP5 models and the 20CR reanalysis dataset. Nevertheless, the effects of scarce and missing records during the early periods, as well as inhomogeneities caused by changes to observing systems locally, were not sufficiently considered in most of the early works. For the first time, Cao et al. (2013) established a set of homogenized long-term monthly mean SAT series from 18 stations, mainly in eastern China, based on the RHtest method (Wang and Feng, 2013). An extended dataset of 32 stations with improved coverage over China was recently developed (Cao et al., 2017). These undoubtedly improved the database for climate change studies in the region.

However, some inhomogeneities remained in the recently developed dataset. For instance, as discussed by Cao et al. (2017), the SAT series at Nanjing, eastern China, remained questionable, as it showed slight cooling while all nearby stations showed significant warming during the past century. Possible reasons are as follows: First, the preconditions applied for the data processing might be too strict, e.g., a detected break point needed to be confirmed by the metadata (Cao et al., 2013). Second, there were no reference data for many cases for the early period before 1950, due to sparse observations. Third, incomplete metadata, especially before 1950, might further increase the probability of overlooking some detected break points. Therefore, it is beneficial to further adjust the long-term SAT series in order to improve the dataset for studying large-scale climate change in the region.

The present report introduces a further-adjusted long-term temperature series in China based on the MASH method, serving as a call for applications of the new data (available online). Section 2 describes the data and methods. Section 3 demonstrates the detected outliers, break points and inhomogeneous biases in the previously published data. Section 4 compares the new data with the previous in terms of long-term trends. Section 5 concludes the report.

2. Data and methods

2.1. *Updated SAT series*

The monthly SAT series at 32 stations from the start of observation to 2015, homogenized by Cao et al. (2017), are available from the China Meteorological Data Service Center (CMDC, http://data.cma.cn/). We updated the time series with instrumental temperature records in 2016 collected from the CMDC, Hong Kong Observatory, Macao Meteorological and Geophysical Bureau, and Central Weather Bureau of Taiwan. The dataset that was updated is hereafter referred to as the "previous dataset".

The number of stations increased from 1 in 1873 to 28 in 1924 and 32 in 1942. To avoid using the early period of scarce data to facilitate application of the MASH software (Szentimrey, 1999), we applied MASH to the 28 stations with continuous records since 1924. The basic information on the stations is listed in Table 1.

2.2. *MASH*

MASH is an iterative procedure designed to detect and adjust possible break points through mutual comparisons of a number of series with similar climate variability based on statistical tests of hypotheses at a given significance level. Any series is not necessarily homogeneous. Several difference series are constructed from the candidate and weighted reference series. The optimal weighting is determined by minimizing the variance of the difference series, in order to increase the efficiency of the statistical tests. The inhomogeneity of the difference series can be characterized by the test statistic, which should be smaller than the critical value via a Monte Carlo method and cases of homogeneity at the given significance level. MASH has been widely applied to homogenize climate data in many studies worldwide (Manton et al., 2001; Lakatos et al., 2008; Rasol et al., 2008; Birsan and Dumitrescu, 2014). It has also been applied to homogenize temperature series in China, and proved a suitable technique via a number of applications of the homogenized data (Li and Yan, 2009; Li et al., 2015b, 2016).

In the present study, the latest version of MASH (v3.03) was used. Different from previous versions, MASH v3.03 starts with a preliminary examination of the annual series and uses the detected breaks as preliminary information (used as proxy metadata) for the standard procedure of MASH for monthly data. The new developments of automatic procedures make the homogenization easier for the end user. The fourth is some developments for daily data, including some new program procedures for missing data completion and data quality control. The mathematical and technical details are introduced in the online manual at http://www.met.hu/en/omsz/rendezvenyek/homogenization_and_interpolation/software/. The additive model is applied to temperature series underlying a normal distribution. The significance level for testing break points via the Monte Carlo method is $\alpha = 0.01$. The reference system of nine nearby stations for each candidate station is determined based on their distances to the candidate station. The inhomogeneous sections are

Table 1. Information on the 28 stations used in the MASH analysis.

No.	Station index	Name	Abbreviation	Latitude (°N)	Longitude (°E)	Starting in month/year
1	45005	Hongkong	HK	22.29	114.17	01/1884
2	45011	Macao	MC	22.20	113.53	01/1901
3	50527	Hailar	HLE	49.22	119.75	01/1909
4	50953	Harbin	HEB	45.75	126.77	01/1909
5	53463	Hohhot	HHHT	40.82	111.68	01/1915
6	53772	Taiyuan	TY	37.78	112.55	01/1916
7	54161	Changchun	CC	43.90	125.22	01/1909
8	54342	Shenyang	SY	41.73	123.52	05/1905
9	54471	Yingkou	YK	40.67	122.17	01/1905
10	54511	Beijing	BJ	39.80	116.47	09/1890
11	54527	Tianjin	TJ	39.08	117.07	09/1890
12	54662	Dalian	DL	38.92	121.63	01/1905
13	54765	Yantai	YT	37.48	121.43	01/1905
14	54857	Qingdao	QD	36.07	120.33	01/1900
15	56739	Tengchong	TC	25.02	98.50	01/1916
16	56778	Kunming	KM	25.00	102.65	01/1921
17	57494	Wuhan	WH	30.62	114.13	02/1905
18	57516	Shapingba	SPB	29.58	106.47	01/1924
19	57679	Changsha	CS	28.20	113.08	01/1911
20	57816	Guiyang	GY	26.58	106.73	10/1920
21	58238	Nanjing	NJ	32.00	118.80	01/1905
22	58367	Shanghai	SH	31.20	121.43	01/1873
23	58847	Fuzhou	FZ	26.08	119.28	01/1905
24	59134	Xiamen	XM	24.48	118.07	01/1915
25	59287	Guangzhou	GZ	23.17	113.33	03/1912
26	59358	Tainan	TN	23.00	120.22	01/1897
27	59431	Nanning	NN	22.63	108.22	01/1922
28	59559	Hengchun	HC	22.00	120.73	01/1897

adjusted to the latest homogeneous part of the SAT series.

A linear trend is estimated via the least-squares linear fitting method, to assess the long-term change in the SAT series. The t-test is used to assess the significance of the trend at $\alpha = 0.05$.

3. Inhomogeneities in the previous data

3.1. *Outliers*

Figure 1a shows the number of potential outliers in the previous data for each month at each station, estimated by the MASH procedure. To facilitate discussion, we define an erroneous outlier in the present study if the potential outlier exhibits an inhomogeneous shift from the neighboring year larger than 1.5°C. There are 33 monthly temperature records from 12 stations detected as erroneous outliers. The station HHHT in northern China contains the most (nine outliers in six monthly series). There are no outliers at the other 16 stations.

To highlight what an outlier is, we take an example of SAT for January 1951 at XM station. As Fig. 1b shows, the SAT record of January 1951 at XM is of an anomaly larger than 5°C, far beyond the average of those at the nine reference stations, which are all negative anomalies for the same month. Figure 1c shows the new SAT series compared with the previous for January at XM, highlighting the inhomogeneous record in 1951. Obviously, the further-adjusted SAT series for January at XM becomes consistent with those at the reference stations. The new series has a warming trend of 1.67°C (100 yr)$^{-1}$, compared with 1.52°C (100 yr)$^{-1}$ in the previous data.

3.2. *Break points*

Figure 2a shows the number of inhomogeneous break points in the SAT series for each month at each station during 1924–2016. To aid understanding, we set those with an inhomogeneous shift larger than 0.5°C as a meaningful break point. There are 152 meaningful break points in the monthly SAT series at 26 stations. The MC station has the most (24 break points in 10 monthly series). There is no break point detected for the HC and TN stations in Taiwan.

To help understand the meaningful inhomogeneous biases, we draw attention to the SAT records around the 1940s at NJ. Figure 2b shows the annual SAT anomalies (from the 1971–2000 mean climatology) during 1924–2016 at NJ and

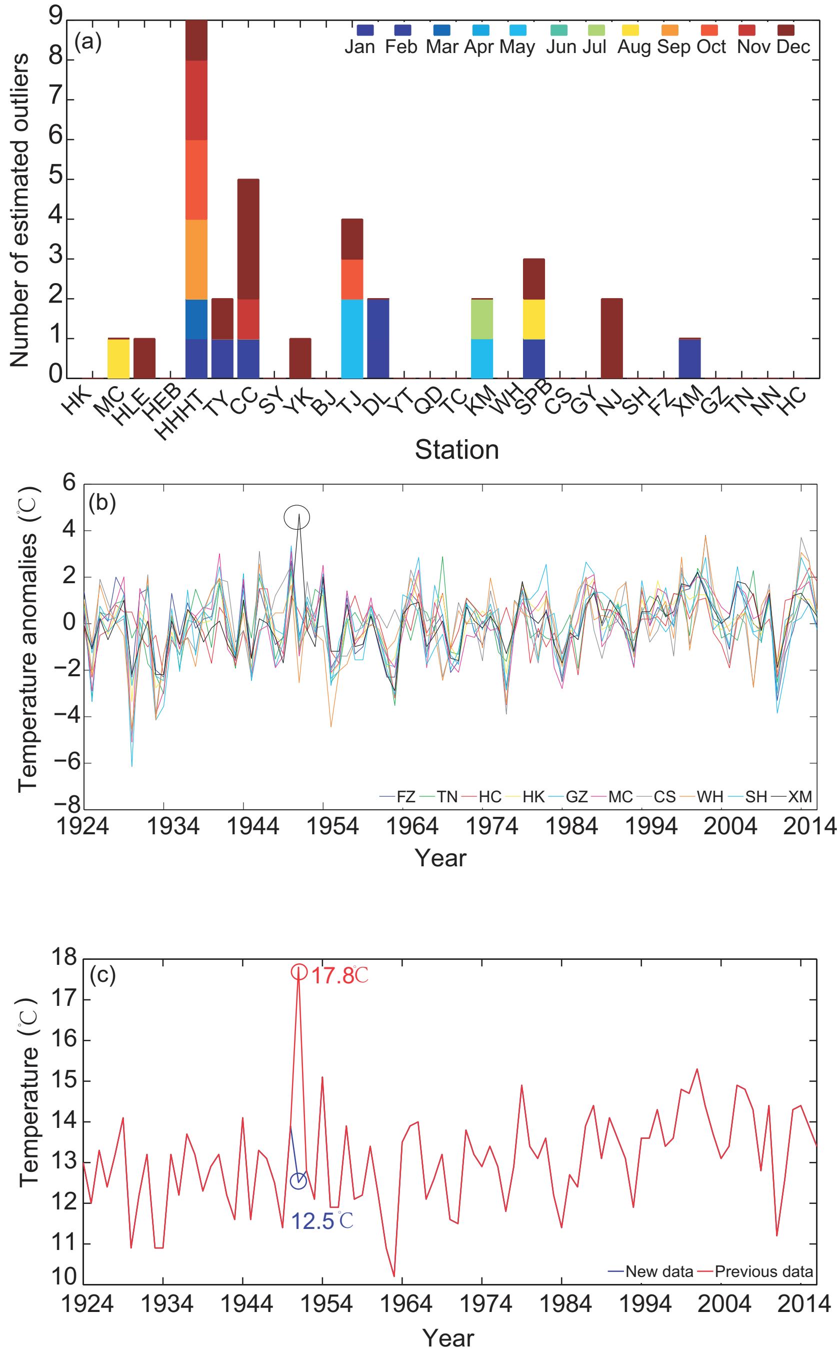

Fig. 1. (a) Number of erroneous outliers in the SAT records for each month at each station. (b, c) Outlier case for January at XM: (b) SAT anomalies in the 1971–2000 climatology for January at XM and nine reference stations in the previous data; (c) the previous and new January SAT series at XM.

nine reference stations from the previous dataset. Obviously, there are unusual warm peaks around the 1940s and the earlier years at NJ, compared with the SAT anomalies at the surrounding reference stations. Figure 2c compares the adjusted series with the previous one. The new series becomes more coherent with the surrounding series around the 1940s. The inhomogeneous biases in the previous data exist mainly before the 1950s. The new SAT series at NJ shows a warming trend of 0.82°C (100 yr)$^{-1}$, compared with −0.23°C (100 yr)$^{-1}$ based on the previous data. As discussed in Cao et al. (2013, 2017), many stations moved from a city to a rural location, causing a drop in temperature records around that time; and hence, most of the adjusted series showed an enhanced warming trend. However, there were no metadata for Nanjing around these early times, and hence no adjustment was made for this station by Cao et al. (2013).

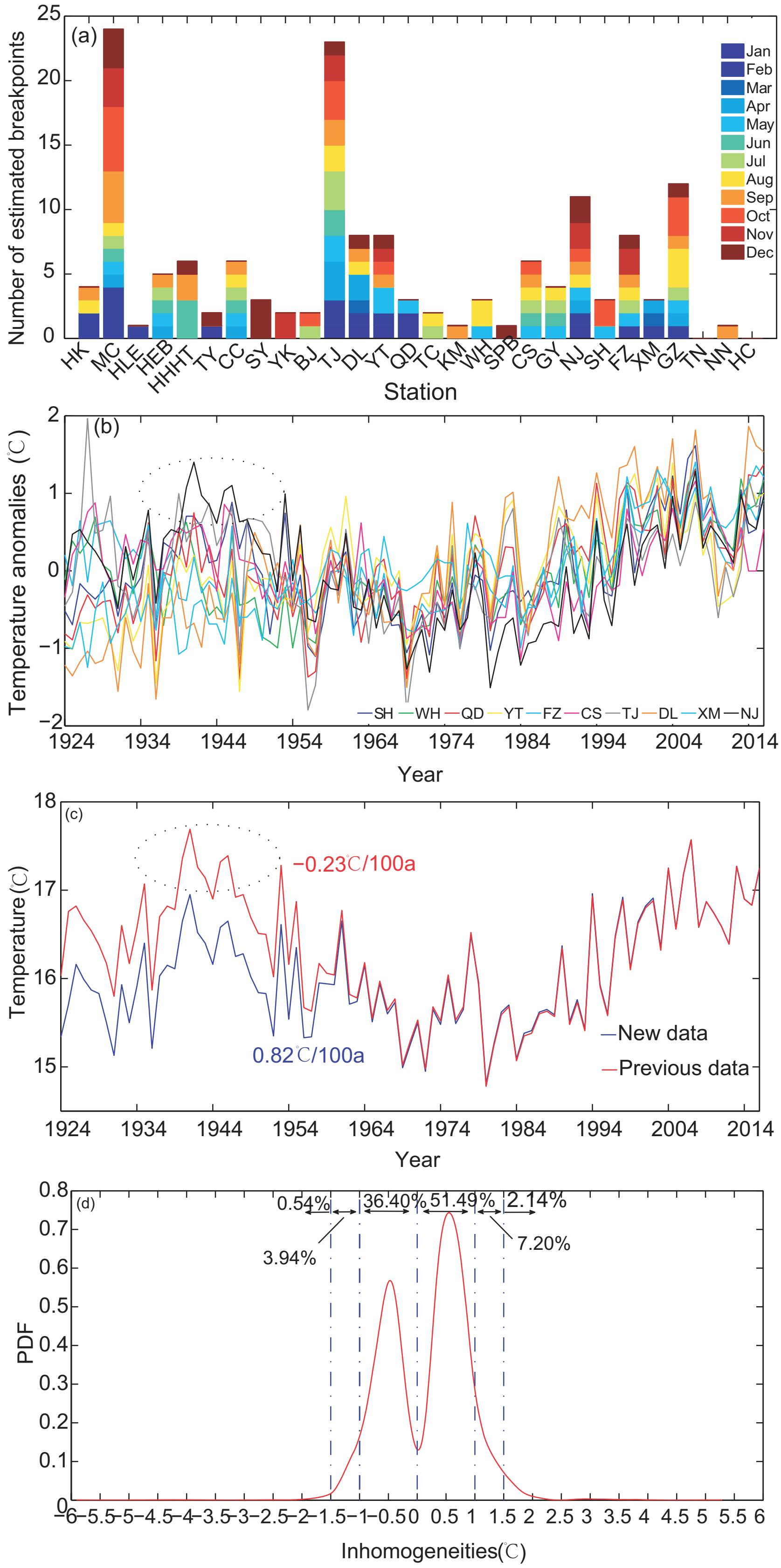

Fig. 2. (a) Number of break points in the SAT records for each month at each station. (b, c) Inhomogeneity case for the annual SAT series at NJ: (b) previous annual SAT anomalies at NJ and nine reference stations; (c) previous and new annual SAT series at NJ. (d) PDF of all the monthly adjustments based on MASH.

3.3. *Probability distribution of inhomogeneous biases*

There are 5673 monthly SAT records adjusted based on MASH, of which 3358 are of an absolute value larger than 0.5°C, about 10% of the total monthly records. Figure 2d shows the probability density function (PDF) of the monthly adjustments. A majority (4986 or 88%) of the adjustments are between −1°C and 1°C, with two probability peaks around −0.5°C and 0.5°C, respectively. As most of the adjustments are for the early period, they should influence the estimation of the long-term trend in the climate series.

4. Comparing long-term trends between the previous and new data

In order to show the influence of inhomogeneities remaining in the previous data on the estimation of long-term trends, Fig. 3 shows the geographical patterns of the linear trends in the annual SAT series during 1924–2016, compar-

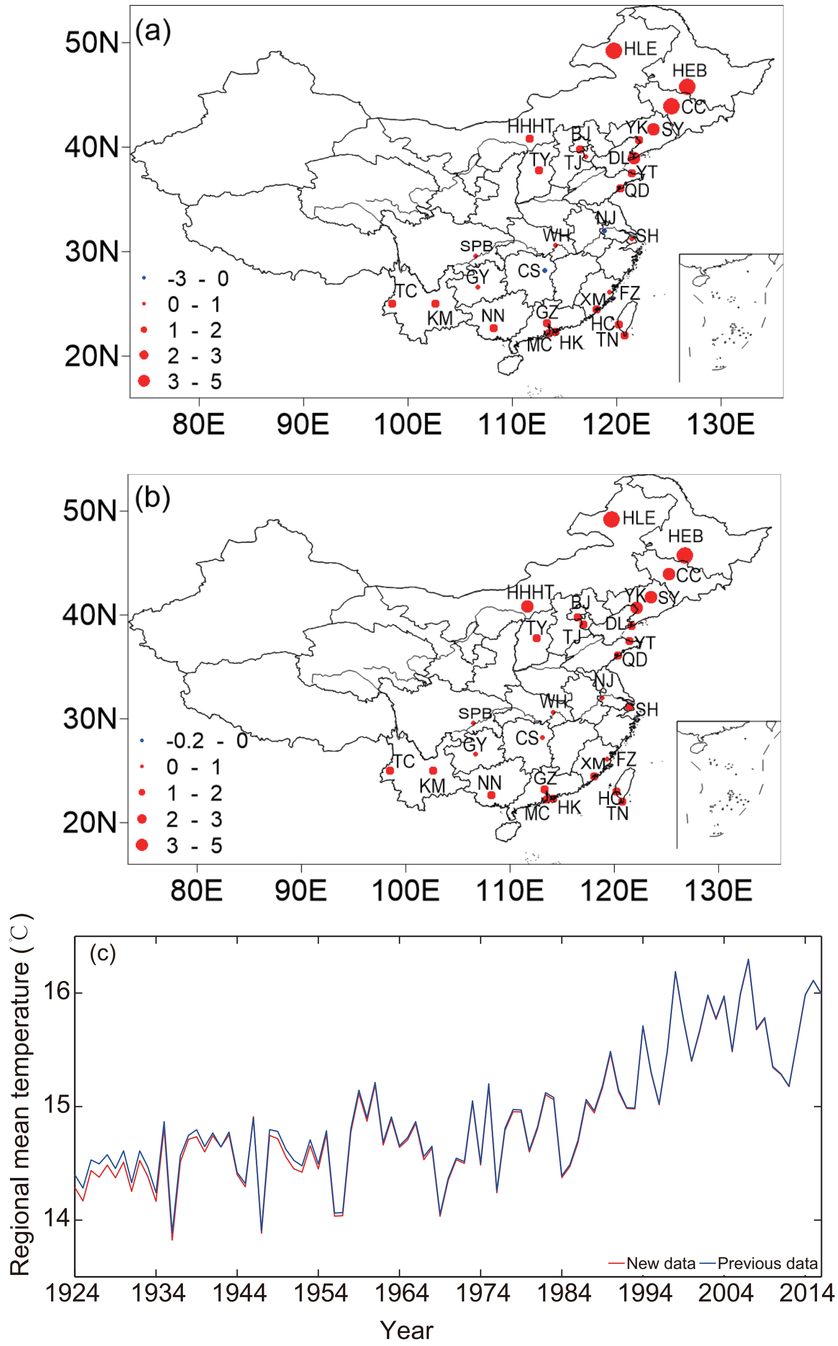

Fig. 3. Linear trends in the annual SAT series at 28 stations during 1924–2016 based on the (a) previous and (b) new data. (c) Regional mean series compared between the previous and new data.

ing the previous with the new data. The new data show significant warming trends at all the 28 stations; however, the previous data exhibit negative trends at CS and NJ, which are inconsistent with surrounding observations. There is a smaller range of warming trends [from 0.48°C (100 yr)$^{-1}$ to 3.57°C (100 yr)$^{-1}$] in the new data than that in the previous data [from −0.23°C (100 yr)$^{-1}$ to 4.02°C (100 yr)$^{-1}$]. The warming trends are large in northeastern China, up to 3.57°C (100 yr)$^{-1}$, and small in south-central China, down to 0.48°C (100 yr)$^{-1}$, based on the new data. Compared with the new data, the linear trends in the previous data are underestimated for 13 stations and overestimated for another 13 stations. It is therefore suggested that the further-adjusted data better represent the large-scale pattern of climate change during the last century in this region.

In terms of the regional mean annual SAT series, the previous data exhibit a slightly higher level of SAT before the 1950s (Fig. 3c). Hence, the new data lead to a slightly larger regional mean warming trend [1.65°C (100 yr)$^{-1}$] than the previous result [1.57°C (100 yr)$^{-1}$].

To keep utilizing the earlier data at the longer-term stations, we adjust the earlier part of the series as a whole to the homogenized part since 1924 for the stations with earlier data. The linear trend of the annual SAT series from the starting year to 2016 at each station is calculated and compared between the previous and the new data. Two stations, CS and NJ, show negative trends [−0.15°C (100 yr)$^{-1}$ and −0.01°C (100 yr)$^{-1}$] based on the previous data. The new data exhibit significant warming trends all over China. The further-adjusted data show a range of trends between 0.36 and 3.56°C (100 yr)$^{-1}$, smaller than the previous result [between −0.15°C (100 yr)$^{-1}$ and 3.98°C (100 yr)$^{-1}$]. Therefore, it is suggested that the previous data include more local signals and the further-adjusted long-term SAT series should be a better representation of the large-scale pattern of climate warming in China than the previous data.

5. Summary and discussion

A set of further-adjusted long-term temperature series in China back to the 19th century based on MASH has been established. This dataset contains 28 stations, mainly over central and eastern China, and extends from the start date of observations to December 2016. We found 33 monthly records as erroneous outliers and 152 inhomogeneous break points in the previous dataset, and hence further adjusted about 10% of the monthly records during 1924–2016 at these stations.

The new data show a smaller range of warming trends among the 28 stations during 1924–2016 [0.48°C–3.57°C (100 yr)$^{-1}$] than the previous result. The further-adjusted data should therefore be a better representation of the large-scale pattern of climate change during the last century in the region. The regional mean SAT series shows a warming trend of 1.65°C (100 yr)$^{-1}$ during 1924-2016, larger than the previous result [1.57°C (100 yr)$^{-1}$].

It remains arguable whether multi-decadal climate variability can reverse the century-scale warming trend at individual stations. Uncertainty remains for the long-term meteorological series due to vague and incomplete data sources in earlier times, measurement biases, site relocations, urbanization in recent decades, and so on. The MASH-based adjustments are based on statistical comparative analyses with neighboring station observations. Further physical validation needs to be carried out via applications of the new data in as many regional climate studies as possible.

While the present paper is aimed at homogenization of SAT series, MASH is also applicable to long-term series of other meteorological elements, e.g., precipitation (Li et al., 2015a) and wind speed (Li et al., 2011) for Beijing. Homogenized long-term precipitation and wind observations in China are expected to be produced in the near future.

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Authors and contributions

Zhen LI: data processing and paper writing;

Zhongwei YAN: supervising data analysis and finalizing the manuscript;

Lijuan CAO and P. D. JONES: producing previous data and discussing the results and paper.

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