

# Construction of the homogenized temperature series during 1910–2014 and its changes in Hunan Province

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**Abstract:** Based on the statistical method and the historical evolution of meteorological stations, the temperature time series for each station in Hunan Province during 1910–2014 are tested for their homogeneity and then corrected. The missing data caused by war and other reasons at the 8 meteorological stations which had records before 1950 is filled by interpolation using adjacent observations, and complete temperature time series since the establishment of stations are constructed. After that, according to the representative analysis of each station in different time periods, the temperature series of Hunan Province during 1910–2014 are built and their changes are analyzed. The results indicate that the annual mean temperature has a significant warming trend during 1910–2014 and the seasonal mean temperature has the largest rising amplitude in winter and spring, followed by autumn, but no significant change in summer. Temperature variation over Hunan Province has several significant warm-cold alternations and more frequent than that in whole China. Annual and seasonal mean temperatures except summer and autumn have abrupt warming changes in the recent 100 years. The wavelet analysis suggests that the annual and four seasonal mean temperatures in recent 100 years have experienced two climatic shifts from cold to warm.

**Keywords:** Hunan Province; homogeneity; temperature series; change characteristics

## 1 Introduction

The studies on climate change have paid more and more attention to the long-term trends of surface air temperature (SAT). Both long-term and homogeneous instrumental temperature data have been essential for assessing global warming and regional climate change over past decades (Jones *et al.*, 1999). Significant progress has been made in the use of homogeneous SAT datasets to estimate global warming, and several SAT datasets have been compiled (Peterson and Vose, 1997; Hansen *et al.*, 2010; Lawrimore *et al.*, 2011; Jones *et al.*, 2012). Based on

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these datasets, The Fifth Assessment Report of Intergovernmental Panel on Climate Change (IPCC) pointed out that global mean SAT rose  $0.85^{\circ}\text{C}$  during 1880–2012 (Qin *et al.*, 2014).

In recent years, the compilation and construction of long-term and homogeneous instrumental SAT series have been on-going processes over China (Tang and Ren, 2005; Li *et al.*, 2010; Cao *et al.*, 2013). But in regional scale, long-term and homogeneous instrumental SAT data is still lacking. Taking South Central China as an example, Duan (1989) utilized tree-ring data to construct temperature series in the past 200 years over Hunan Province, and later, based on local chronicles and other historical materials, Duan (1992) analyzed the changes of winter temperature in the past 600 years over Dongting Lake Region. Using temperatures records and related descriptions of cold/warm events recorded in historical documents for South Central China, Wang *et al.* (1998) reconstructed the mean annual temperature series from 1880 to 1996 in this region. Utilizing monthly SAT instrumental records at 33 stations of South Central China, Ren *et al.* (2010) constructed a regional mean SAT series during 1905–2005. Afterward, Zheng *et al.* (2015) reconstructed annual temperature anomalies in South Central China from 1850 to 2008 derived from phenological and natural evidence. Here also has published a number of tree-ring series which instructed the temperature changes in South Central China (Fang *et al.*, 2005; Cao *et al.*, 2012; Zheng *et al.*, 2012; Cai and Liu, 2013), but most of the above series were not constructed by instrumental records and the rest of instrumental series were developed without considering homogeneity due to inconsistent observational schedules in different years, relocations of stations, and missed observations.

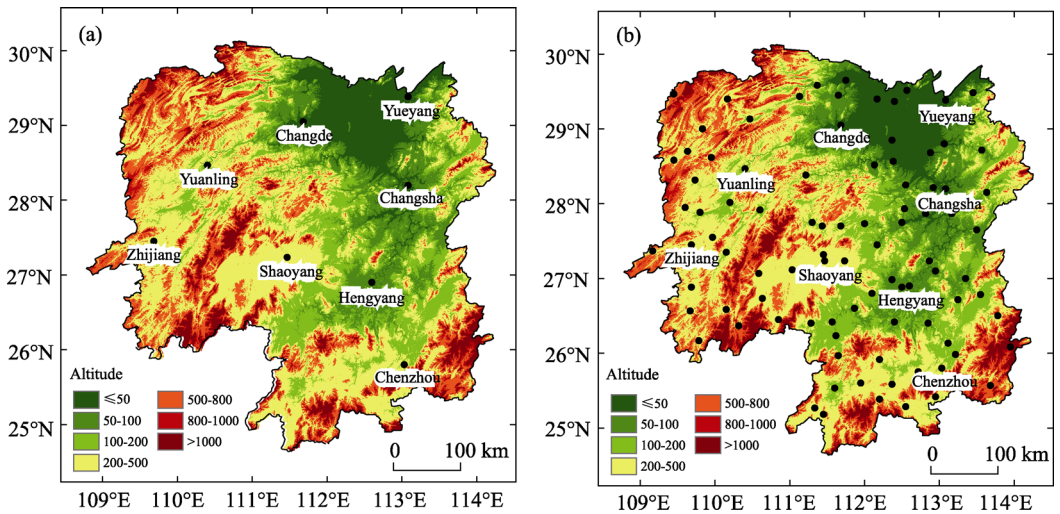
Therefore, it is necessary to further reconstruct the homogeneous instrumental SAT series in Hunan over the past 100 years, particularly given that the temperature data before 1950 is incomplete due to war and other reasons in this region and the inhomogeneity problems of the temperature data in China (Liu and Li, 2003; Li *et al.*, 2003; Li *et al.*, 2004; Li *et al.*, 2009; Cao and Yan, 2011).

In this paper, we systematically adjust the homogeneity of the historic temperature observations, and fill the missing data of each station with regression model based on the adjacent stations' data. After that, the complete series of each station since establishment are built up. Then a representative analysis of temperature series of each station is carried out in order to choose appropriate representative stations for different time periods. Based on the above steps, Hunan's regional temperature series of the recent 100 years are constructed and the change characteristics are analyzed.

## 2 Data

The raw data used in this paper is comprised of three parts.

The first is the monthly temperature data of 8 meteorological stations before 1950 from Hunan Provincial Meteorological Archives (The geographical distribution shown in Figure 1a). The temperature observation of Changsha and Yueyang stations began in 1909 and other 6 stations began during 1932–1942, due to war and other reasons, each station had several missing records at some stages (shown in Table 1). The second is the monthly temperature data of 96 meteorological stations in Hunan Province since 1951 (The geographical distribution shown in Figure 1b). The third is the monthly temperature data of Wuhan, Nanjing, Hangzhou, Chongqing and Guangzhou from the GHCN dataset (Global Historical



**Figure 1** Geographical distribution of the observation stations (a. stations with data before 1950; b. all the stations after 1951)

**Table 1** Information of 8 meteorological stations with data before 1950 in Hunan Province

Station No.	Station name	Starting time (month/year)	Missing periods in record (month/year)	Missing months
57584	Yueyang	12/1909	12/1916–01/1917 12/1917–01/1918 03/1920–07/1921 12/1921–05/1922 12/1924 05/1938–12/1950	180
57655	Yuanling	07/1942	02/1949–09/1949 11/1949–12/1950	22
57662	Changde	08/1932	12/1934 11/1938–03/1946 06/1949–12/1949	97
57679	Changsha	06/1909	04/1910–09/1910 01/1923 10/1924 11/1938–03/1939 09/1939–10/1939 10/1941 12/1941–03/1942 07/1943 05/1944–03/1946 02/1947 05/1949–08/1949	49

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Station No.	Station name	Starting time (month/year)	Missing periods in record (month/year)	Missing months
57745	Zhijiang	01/1937	03/1938–05/1938 09/1949–05/1950	12
57766	Shaoyang	09/1936	06/1944–09/1950	76
57872	Hengyang	01/1933	01/1939–12/1939 10/1941 01/1944–06/1946 01/1948–12/1949	67
57972	Chenzhou	12/1936	11/1941 06/1944–07/1946 07/1949–12/1950	45

Climatology Network, monthly version3 (Lawrimore *et al.*, 2011) through systematical quality-control and homogeneity-adjusted) and it is treated and selected as reference data for homogeneity test of the long time station temperature series (mainly for Changsha and Yueyang) in Hunan Province.

3 Construction of temperature series

3.1 Homogeneity test and correction

The reliability and accuracy of climate data is the basis of climate change research. Change of observation instrument, station relocation and other reasons would affect the homogeneity of observation data (Li *et al.*, 2003). Therefore, the homogeneity test and correction to the temperature series of each station is the prerequisite of analyzing the temperature change characteristics.

To carry out the homogeneity test in temperature series of a station, it is very important to construct a reasonable reference series by using the data of the adjacent stations, because the reference series is an important indicator of local climate and any significant difference from the local climate signal would be assumed to be discontinuity (Li *et al.*, 2003). The meteorological stations in Hunan were relatively few before 1950 and increased significantly since 1951. In order to ensure the nearest station to be chosen to construct the reference series, the homogeneity test and correction in this paper are divided into two parts. Firstly, the temperature series of all 96 stations during 1951–2014 will be carried out of homogeneity test and correction by using the adjacent stations in Hunan as the reference, and secondly, 8 stations’ series during 1910–1950 will be carried out by using both the adjacent stations in Hunan and other stations in the surrounding provinces as reference.

3.1.1 Homogenization of temperature series after 1951

The homogeneity of the annual mean temperature, annual mean maximum temperature and annual mean minimum temperature series of all 96 stations during 1951–2014 in Hunan has been tested with the two-phase regression model (Lund and Reeves, 2002) and the preliminary discontinuities in these time series are obtained. Likewise, the time series of the three types of temperature above at monthly scale have also been tested with the same method and

the potential discontinuities are also obtained. Then the common inhomogeneous points are found out by comparison of preliminary and potential discontinuities. Based on the above two steps, the manual analysis of the different images between each station's series and those of the surrounding stations is carried out, taking the stations' historical evolution into consideration. Finally, it is confirmed that, among the 96 stations, the average temperature series at 33 stations are inhomogeneous with a total of 36 break points; as for maximum temperature, there are 37 break points in 34 stations; and for minimum temperature, 26 break points in 23 stations (shown in Table 2). According to the above test results, all of the inhomogeneous series are corrected.

Figure 2 shows the difference of the linear trend between the original annual mean temperature and that of the adjusted version. It is noticeable that the linear tendency rates in several stations are much higher or lower than adjacent stations before being homogenized, and after being homogenized, the difference becomes smaller. It indicates that the linear tendency rate of homogenized temperature can reflect the local climate change of the station area accurately.

### 3.1.2 Homogenization of temperature series before 1950

The method of homogeneity test for maximum temperature and minimum temperature series of 8 stations in Hunan Province during 1910–1950 is basically the same with the above method, and the only difference is that which stations are selected as the reference series. In view of the fact that there are only 2 stations (Changsha and Yueyang) have over 100 years series in Hunan, no adjacent station in Hunan can be chosen to treat as reference station for homogeneity test of the above 2 stations, so several stations in the surrounding provinces like Wuhan, Guangzhou, etc. from GHCN are selected to construct the reference series of Changsha and Yueyang, but for the other 6 stations which started records during 1932–1942, adjacent stations in Hunan are selected as reference stations for homogeneity test. Finally, the result shows that 3 of 8 stations' maximum temperature series have been confirmed inhomogeneity and there are a total of 3 break points, for minimum temperature there are 2 break points in one station (shown in Table 3).

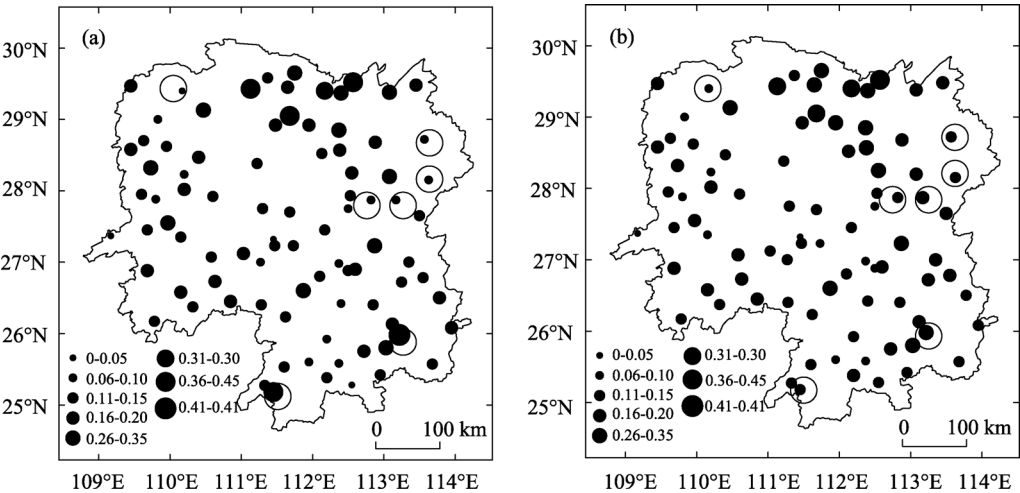
Taking the correction of annual mean minimum temperature series of Changsha as an example, Figure 3 shows the differences of Changsha station's original and reference series. Before 1932 the original series are significant higher than the reference, and the average difference value is 3.5°C; then the value becomes as low as 2.4°C during 1933–1950, and becomes much lower to 1.9°C since 1951. Obviously, the annual mean minimum temperature series in Changsha have two significant break points. Figure 4 shows the different series before and after adjustment, the linear trend of the original and corrected series exhibits great differences. Before adjustment the temperature shows a descending trend with a rate of  $-0.05^{\circ}\text{C}/\text{decade}$ , while after adjustment it becomes a significant ascending trend by  $0.17^{\circ}\text{C}/\text{decade}$ . Obviously, the adjusted annual mean minimum temperature series demonstrates a higher long-term trend, which is more reasonable than those of the adjacent stations. Similar methods are also applied to the rest station series for the purpose of homogenization.

### 3.2 Interpolation for filling missing data before 1950

Eight meteorological stations have temperature records before 1950 in Hunan Province, but some of the data in a few years were missing or incomplete due to war and other reasons.

**Table 2** Break points of temperature series during 1951–2014 at meteorological stations in Hunan Province (“—” denotes no break points)

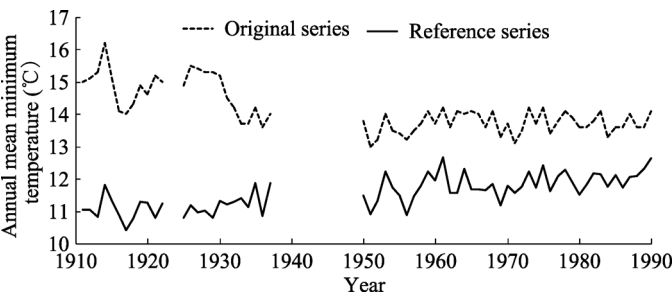
Station No.	Station name	Break points of average temperature series	Break points of maximum temperature series	Break points of minimum temperature series
57554	Sangzhi	1972	1972	1972
57565	Lixian	1974	1962, 1974	—
57657	Luxi	—	1996	—
57662	Changde	1953	1953	—
57663	Hanshou	1963, 1971, 1980	1971, 1980	1963, 1971, 1980
57666	Taojiang	1980	1980	1967, 1980
57671	Yuanjiang	—	1968	1968
57674	Yiyang	—	1961	—
57679	Changsha	—	1963	1963
57682	Pingjiang	1987	1987	1987
57687	Wangchengpo	1974	1974	—
57688	Liuyang	2000	1960, 2000	2000
57740	Fenghuang	1970	1970	—
57752	Xupu	1958, 1966	1966	—
57760	Lengshuijiang	1981	1981	1981
57761	Xinhua	1959	1959	1959
57768	Xinshao	—	1964	—
57771	Shaoshan	1974	1974	1974
57772	Xiangxiang	1965	—	—
57773	Xiangtan	1982	1982	1982
57777	Hengshan	1965	—	—
57779	Youxian	1976	—	—
57780	Zhuzhou	1975	1975	1975
57781	Liling	1963	1963	1963
57846	Suining	1963	1963	1963
57860	Shaoyangxian	2000	2000	2000
57866	Yongzhou	1953	1953	1953
57867	Dong'an	1963	—	—
57871	Hengyangxian	1962	—	—
57872	Hengyangshi	1960	1960	1960
57874	Changning	1974	1974	1974
57881	Anren	1967	1967	1967
57889	Guidong	1970	1970	—
57965	Daoxian	—	1964	—
57966	Ningyuan	—	1965	1965
57971	Xintian	1972	—	—
57975	Lanshan	1960	1960	—
57978	Linwu	1978	1978	1978
57981	Zixing	1992	1992	1992
59063	Jianghua	1989	1989	1989



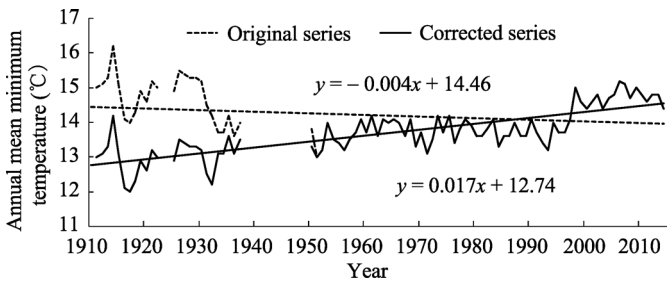
**Figure 2** Distribution of the linear tendency of annual mean temperature during 1961–2014 in Hunan Province ( $^{\circ}\text{C}/10\text{a}$ ) (“ $\circ$ ” denotes the stations in which linear tendency rates are significantly higher or lower than the adjacent stations before homogenized) (a. before homogenized; b. after homogenized)

**Table 3** Break points of temperature series during 1910–1950 at meteorological stations in Hunan Province (“—” denotes no break points)

Station No.	Station name	Break points of maximum temperature series	Break points of minimum temperature series
57584	Yueyang	1937	—
57679	Changsha	1950	1932,1950
57872	Hengyang	1947	—



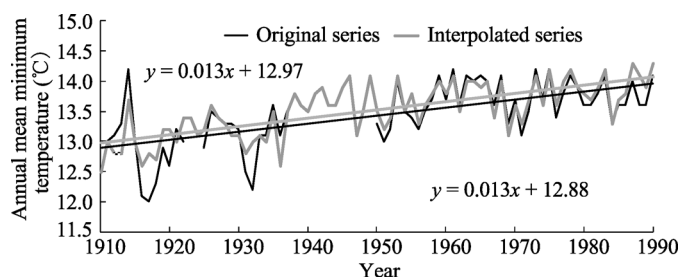
**Figure 3** The original and reference annual mean minimum temperature series in Changsha during 1910–1990 (For war and other reasons, part of data are missing)



**Figure 4** The original and adjusted annual mean minimum temperature series in Changsha during 1910–2014

For this reason, the following method is used to carry out the interpolation to fill the missing data. A adjacent station in Hunan which has the best correlation with the target station is selected as a reference station and a regression equation for reference and target stations is built using each month's average maximum and minimum temperature series after being homogenized, thus the missing data of all 8 stations are filled with interpolation month by month. Due to the significant warming since 1990 in Hunan and the difference of temperature ascending rates caused by different urbanization process, the above equations only use the temperature data before 1990. All the equations are based on monthly data and significant at the 0.01 level. Annual and seasonal values and were computed by the interpolated value of each month.

Taking the annual mean minimum temperature series of Changsha as an example for the assessment of interpolation, Figure 5 shows the differences of Changsha station's original and interpolated series. The two series are highly correlated and correlation coefficient gets to 0.857, linear trend analysis shows a significant upward trend and a slightly difference of ascending rate in the two series, T-test and F-test shows there is no significant difference between the mean and the variance of the two series.



**Figure 5** The original and interpolated annual mean minimum temperature series in Changsha during 1910–1990

### 3.3 Construction of temperature series during 1910–2014

The number of meteorological stations in Hunan changes from time to time. Only 2 stations (Changsha and Yueyang) had temperature records during 1910–1931, other 6 stations began to have meteorological observation one after another during 1932–1942 (shown in Table 1). The number of stations was maintained at 8 during 1943–1950, then increased rapidly from 1951 to 1960 and remained stable since 1961. Under this situation, the correlation analysis is used to find out the best representative stations (That is, the higher the correlation coefficient with the average of all 96 stations, the better the representation), and based on the above analysis and taking geographical distribution into account, representative stations are selected as many as possible to construct temperature series of Hunan Province during 1910–2014.

Result of correlation analysis shows that the correlation coefficient with the average of all 96 stations in Changsha is higher than Yueyang and the average of the above 2 stations. That means representation of Changsha's temperature series is better than Yueyang and the average (shown in Table 4). Therefore, the temperature series of Hunan Province during 1910–1936 is constructed based on the Changsha's series (hereinafter referred to as Changsha). Due to the uniform geographical distribution of 8 stations which had temperature re-

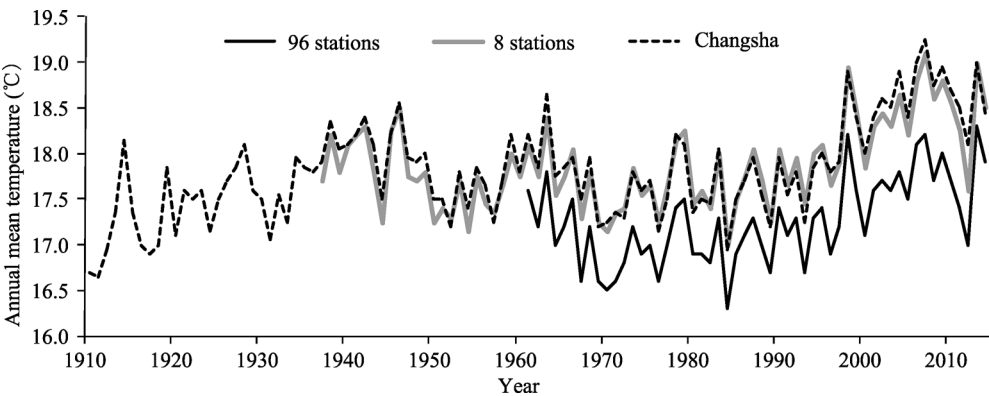


cords before 1950 and their good representation, the temperature series of Hunan Province during 1937–1960 are constructed based on the average of the above 8 stations (hereinafter referred to as 8 stations), and temperature series during 1961–2014 are calculated by the average of all 96 stations (hereinafter referred to as 96 stations). Based on the above steps, the regression models for Changsha with 96 stations and 8 stations with 96 stations are established to extend series of 96 stations to 1910 month by month, and the monthly temperature series of Hunan Province during 1910–2014 are constructed.

**Table 4** Correlation coefficient of monthly mean temperature in Changsha, Yueyang and their mean values with the average of 96 stations from 1961 to 1990

	1	2	3	4	5	6	7	8	9	10	11	12
Changsha	0.977	0.982	0.981	0.959	0.973	0.970	0.958	0.926	0.957	0.962	0.982	0.974
Yueyang	0.955	0.966	0.963	0.908	0.905	0.888	0.872	0.902	0.906	0.894	0.956	0.919
Average of 2 stations	0.971	0.977	0.978	0.944	0.956	0.948	0.938	0.938	0.945	0.943	0.975	0.955

Figure 6 shows annual mean temperature series of Changsha, 8 stations and 96 stations. Due to the absence of the average temperature data before 1950, the average temperature series of Changsha and 8 stations are replaced by the mean value of the maximum and minimum temperature. The mean temperature of Changsha and 8 stations are highly correlated with 96 stations and the correlation coefficients are 0.955 and 0.981 respectively. Obviously, the 105 years series of 96 stations extended by Changsha and 8 stations is reasonable and reliable.



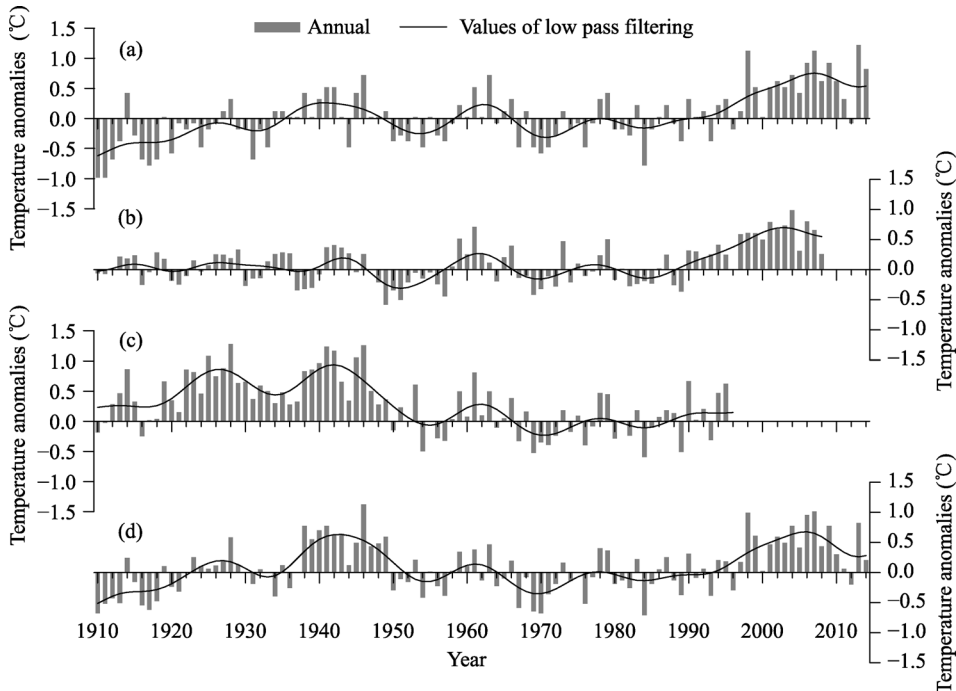
**Figure 6** The annual mean temperature series of Changsha, 8 stations and 96 stations during 1910–2014

## 4 Analysis on temperature changes in Hunan during 1910–2014

### 4.1 Annual mean temperature

The annual mean temperature shows a significant warming trend in Hunan Province with an ascending rate of 0.08°C/decade during 1910–2014 (shown in Figure 7a, exceeded the 0.01 significance level), which is lower than that of the whole China in the same period (CCC, CMA, 2015). The warming rate is 0.16°C/decade during 1961–2014, which is 2 times that of 1910–2014, and 2013 is the hottest year since 1910 in Hunan province. In the latest 18 years (1997–2014), 17 years’ mean temperature anomalies are positive among which 13 years are

in the warmest 18 years since 1910. In the past 100 years, there are 3 obvious warming periods: the first is from the mid-1930s to the end of the 1940s, the second from the end of the 1950s to the mid-1960s, and the last from the early 1990s to present.



**Figure 7** Annual mean temperature anomalies during 1910–2014 in Hunan Province and comparison with other series (a. annual temperature reconstruction; b. annual temperature anomalies derived from phenological and natural evidence during 1910–2008 in South Central China (Zheng *et al.*, 2015); c. South Central China annual temperature anomalies during 1910–1996 (Wang *et al.*, 1998); d. regional mean temperature anomalies from CRU gridded data during 1910–2014 in Hunan Province)

Comparison of the reconstructed series with others (Figures 7b–7d) demonstrated that the reconstruction matched well with the data derived from phenological and natural evidence in South Central China (Figure 7b), especially in the decadal variations and most of the interannual variations. The reconstructed and derived data both revealed a warm interval of greater than 10 years during the 1930s–1940s, an evident cold decade around 1950, an evident warm decade around 1960, and unprecedented warming beginning in the 1990s. The reconstruction here also matched well with the regional mean (Figure 7d) from the Climatic Research Unit (CRU) gridded temperature data from 1910 in most of the interannual and decadal variations, except for a slightly lower difference before the late 1940s. This might be caused by the different procedures of homogenization and the spatial interpolation using observed temperatures outside of Hunan Province in the CRU gridded data, because very few observations were available from the early 1910s to mid-1930s as well as the late 1930s to late 1940s in this area due to social unrest and war. But the different multi-decadal variations and trend are significant between our reconstruction and the observed temperature in South Central China from 1910 to 1950 (Figure 7c), that might be due to the fact that the homogenization was not carried out when the temperature series was constructed in South Central China.

The Mann-Kendall method (Wei, 1999) is applied to test the annual mean temperature se-

ries of Hunan Province during 1910–2014, showing that there is a significant abrupt warming point at 1998 (Figure omitted). The result of Morlet wavelet transformation (Wei, 1999) indicates that the short period oscillation is not obvious and a 20-year period oscillation maintained until 1980. In addition, there is a long periodic oscillation of 50 years maintained during 1910–2014. It means that the annual mean temperature in Hunan Province during 1910–2014 has experienced two climatic shifts from cold to warm, with a cold stage before 1930, warm from 1930 to 1960, cold during 1960–1990 and warm again after 1990 (Figure omitted).

4.2 Seasonal mean temperature

The mean temperature series of winter, spring and autumn show a significant warming trend during 1910–2014 and the ascending rate of winter is the largest, but not obvious in summer. The mean temperature series of winter, spring and autumn also show a significant warming during 1961–2014, but the biggest is in spring, and also not obvious in summer (shown in Table 5). In the past 100 years, there are two obvious warming periods in winter: the first is in the early and mid-1960s, and the second is from the early of 1990s to present (shown in Figure 8a). Abrupt change test shows that there is a significant abrupt warming point in the year of 1987 (Figure omitted). In spring, there are three obvious warming periods: the first is from the late 1920s to the late 1940s, the second from the end of the 1950s to the mid-1970s, and the last from the early 1990s to present (shown in Figure 8b). There is a significant abrupt warming point with the year of 1997 (Figure omitted). In summer, the temperature anomalies are mainly positive from the mid-1920s to the late 1960s and display a descending trend until the 2000s (shown in Figure 8c). There are two significant abrupt warming points in 1933 and 2009 and an abrupt descending point in 1957. In autumn, the mid- and late 1920s and from the mid-1930s to the mid-1940s are the two obvious warm periods. Since then the temperature shows a fluctuation until the mid-1990s, followed by another warm period till today (shown in Figure 8d), and there are also two significant abrupt warming points with the year of 1926 and 2004 and an abrupt descending point in 1947 (Figure omitted).

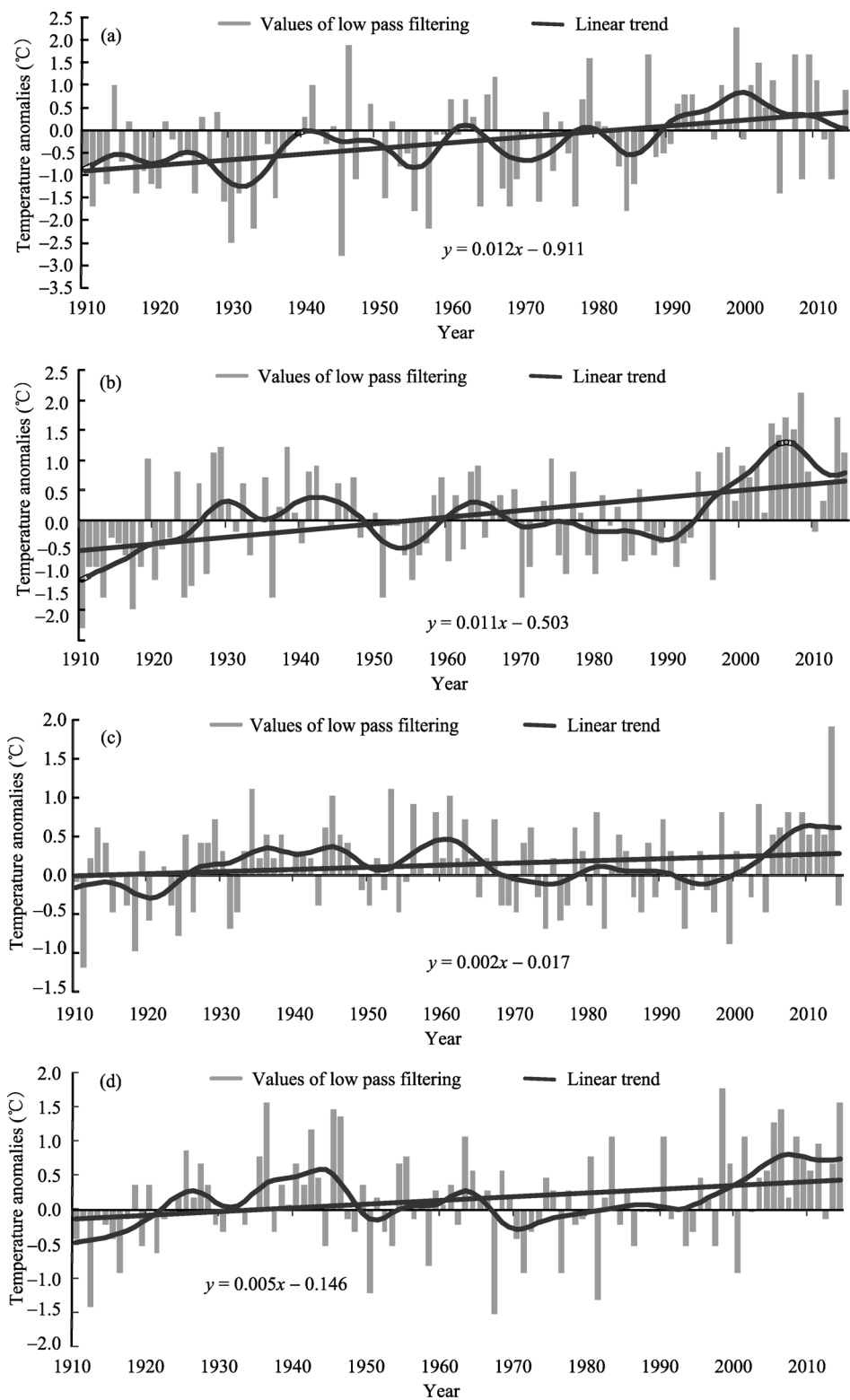
**Table 5** Seasonal temperature linear tendency rates for 1910–2014 and 1961–2014 in Hunan Province (\*\* and \* denote 0.01 and 0.05 level of significant trends, respectively)

	Winter	Spring	Summer	Autumn
Ascending rate during 1910–2014	0.13 **	0.11 **	0.03	0.05 *
Ascending rate during 1961–2014	0.19 **	0.22 **	0.07	0.17 **

The Morlet wavelet transformation is also carried out on each seasonal temperature series during the past 100 years and the results show that there is one long periodic oscillation of 50 years and one intermediate frequency oscillation of 20–30 years and several high frequency oscillations in each season. The 50-year long period oscillation displays that the mean temperature of four seasons has all experienced two climatic shifts from cold to warm during 1910–2014.

5 Conclusions

(1) Construction of long-term homogeneous time series is essential for research on climate change. Based on the technique of two-phase regression and the historical evolution of



**Figure 8** The mean temperature anomalies in winter (a), spring (b), summer (c) and autumn (d) during 1910–2014 over Hunan Province (to average level of 1971–2000)

meteorological stations, the temperature time series for each station in Hunan Province during 1910–2014 are tested for their homogeneity and the temperature series over one third of the total are corrected for inhomogeneity. And after using interpolation and representative analysis in this study, we objectively establish a set of homogenized monthly mean SAT series in Hunan Province back to the early of the 19th century.

(2) The annual mean temperature of Hunan Province shows a significant warming trend during 1910–2014 but its ascending rate is lower than the whole country in the same period. In the background of global warming, the temperature is also alternating between warm and cold in Hunan Province during the past 100 years and more frequently than that in China.

(3) The warming of Hunan Province has a seasonal difference. The mean temperature series of winter, spring and autumn show a significant warming trend during 1910–2014 and the ascending rate of winter is the largest, but not obvious in summer. During 1961–2014, the mean temperature series of winter, spring and autumn also show a significant warming trend but the ascending rate of spring is the largest, and not obvious in summer too.

(4) Abrupt change test show that the annual mean temperature and average temperature in winter and spring all have a significant abrupt warming point during the past 100 years, and the abrupt year of winter temperature is the earliest, then in spring, and the annual mean temperature is the latest. The temperature fluctuations are relatively frequent in summer and autumn, and these two seasons all have two abrupt warming points and one abrupt descending point.

(5) The results of Morlet wavelet transformation show that the annual and seasonal mean temperature series of Hunan Province all have one long periodic oscillation of 50 years and one intermediate frequency oscillation of 20–30 years and several high frequency oscillations. The 50 years long periodic oscillation signal displays that the annual mean temperature occurs two climatic shifts from cold to warm during 1910–2014, also in the four seasons.

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