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Temperature changes derived from phenological and natural evidences in South Central China from 1850 to 2008

J. Zheng[1], Z. Hua[1,2], Y. Liu[1,2], and Z. Hao[1]

[1]Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China

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Correspondence to: Z. Hao (haozx@igsnrr.ac.cn)

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Abstract

The annual temperature anomalies in South Central China from 1850 to 2008 were reconstructed by synthesizing three types of proxies: the spring phenodate of plants recorded in historical personal diaries and observations; the snowfall days extracted from historical archives and observed at meteorological stations; and five tree-ring width chronologies. The instrumental observation data and the leave-one-out method were used for calibration and validation. The results show that the temperature series in South Central China exhibits inter-annual and decadal fluctuations since 1850 (e.g., quasi-15 years and quasi-35 years fluctuations). The first three cold decades were the 1860s, 1890s and 1950s, while 1893 was the coldest year. Except that the three warm decades occurred around the 1850s, 1870s and 1960s, recent warm decades from the 1990s to the 2000s represent unprecedented warming since 1850.

1 Introduction

Long-term temperature data are essential for assessing global warming and regional climate change in the past century (Jones et al., 1999). Significant progress has been made in the use of homogeneous surface air temperature (SAT) datasets to make average hemispheric and global estimates, and several SAT datasets have been compiled (Hansen et al., 2010; Lawrimore et al., 2011; Jones et al., 2012; Rohde et al., 2013); the dataset with the greatest temporal coverage extends back to the 1850s. Although sparse instrumental observations were made in China before 1950 (Tao et al., 1991; Cao et al., 2013), most of them are inhomogeneous due to inconsistent observational schedules among different years, the relocation of stations, and missed observations. In recent decades, many studies have focused on achieving continuous and consistent SAT series for the estimation of national averages in China during the 20th century by bringing together the sparse and inconsistent pre-1950s data with the regular observations after 1950 using data quality control, series infill, and data adjustment for

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homogeneity (Zhang and Li, 1982; Tang and Lin, 1992; Lin et al., 1995; Tang and Ren, 2005; Li et al., 2010; Cao et al., 2013).

Since the instrumental observation data in most of China began at the 1950s, it is important to reconstruct the regional temperature changes based on temperature proxy data with high time resolution (e.g., phenological data, tree-ring chronology, etc.) to extend series to compensate for the deficiency of instrumental observations. However, until now, only one such reconstruction was available in China (Wang et al., 1998). Utilizing the daily mean, maximum, and minimum temperatures, related descriptions of cold/warm recorded in historical documents for East, Central and Southwest China, $\delta^{18}O$ from the ice core in the north of the Tibetan Plateau, and tree-ring data in Tibet, this work reconstructed the mean annual temperature series from 1880 to 1996 in ten regions: Northeast, North, East, South, Taiwan, South Central, Southwest, Northwest, Xinjiang and Tibet. Although these series have become important data to illustrate regional temperature changes in China in the last century (Tang et al., 2009), several flaws remain in the data, as pointed out by the authors. In particular, these flaws are related to the limitations of proxy spatial coverage and the large uncertainty due to the weak relationship between regional temperature changes and proxies for calibration in the reconstruction. Thus, it is imperative to reconstruct a higher-quality dataset on regional temperature change that spans a longer timescale by using more proxies and developing a new approach for the reconstruction. Here, we present a new reconstruction of annual temperature anomalies in South Central China dating back to 1850 by using phenological data and natural evidence.

2 Materials and methods

2.1 Instrumental data

The instrumental data used in the study are China monthly temperature anomalies starting in January 1951 (with respect to 1971–2000 mean climatology). This gridded

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dataset with a spatial resolution of 0.5° × 0.5° was developed and updated by the National Climate Center (Xu et al., 2009) and released by the Chinese Meteorological Administration (http://cdc.nmic.cn/home.do). Because our aim is to reconstruct the annual temperature anomalies in South Central China, the mean annual temperature anomaly for all grids in the study area (Fig. 1) was calculated for calibration and validation.

2.2 Proxy data

Three types of proxies were used in this study to reconstruct temperature changes: phenological data; snowfall day data; and tree-ring width chronologies. The locations of all proxies are illustrated in Fig. 1.

2.2.1 Phenological data

The phenological data include the spring phenodate of plants derived from historical dairies and modern phenological observations. In the traditions of Chinese society, it was customary for scholars to write personal diaries based on their interests, and most of them contain daily weather and related timely phenological phenomena of ornamental plants near their living places. By looking through the detailed descriptions from six historical diaries, we extracted accurate information regarding the recording place, species and spring phenodates (see Table S1 in the Supplement for details). Moreover, observational data were obtained from the Chinese Phenological Observation Network (CPON), which was established in 1963 but interrupted during 1968–1972 and 1996–2002 in most places (Ge et al., 2010). The flowering dates of the sakura (*Prunus yedoensis*) at Wuhan University (31.54° N, 116.36° E) since 1947 (Chen et al., 2008) were also collected. Although the historical phenological data were accurate and objective and could be used as a reliable proxy for temperature reconstruction (Chu, 1973; Aono and Kazui, 2008; Bradley, 2014), they differed from the observational data in the phenological network, which had fixed places, species, and criteria (Chu and Wan, 1980). Therefore, we merged the historical and observational data into the re-

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gional spring phenodate series with homogenized annual anomaly. This approach has been used to reconstruct regional spring phenodate series in the past 150 years in the Yangtze River Delta of China (Zheng et al., 2013). Based on both phenological and temperature data from 1951–2007, the correlation coefficient between annual regional homogenized spring phenodate anomaly and temperature anomaly is −0.53, passing the 0.001 significance level.

2.2.2 Snowfall data

The snowfall days were extracted from historical archives (called "Yu-Xue-Fen-Cun") and weather observations from four stations located in Hunan Province. Yu (rainfall)-Xue (snowfall)-Fen (Chinese length unit, approximately 0.32 cm)-Cun (approximately 3.2 cm) is a type of memo reported to the Emperor by governmental officers during the Qing Dynasty from 1644 to 1911. These memos recorded rain infiltration depth measurements from the dry-wet soil boundary layer to the ground surface taken by digging into the soil with a shovel after rainfall, and the snow depth on the surface after each snowfall event at 273 administrative sites across China. Yu-Xue-Fen-Cun employed a fixed-report format, and the measurements were performed at fixed sites by fixed observers, making it a systematic and homogeneous dataset. Moreover, these data are believed to be highly reliable and accurate (Ge et al., 2005). Thus, the snowfall days recorded in Yu-Xue-Fen-Cun are nearly the same as those recorded by modern weather stations, and these data have been used to reconstruct the variation in winter temperature in the middle and lower reaches of the Yangtze River since AD 1736 (Hao et al., 2012). By combining historical snowfall day records and observational data since 1951, the mean annual snowfall day anomaly series from four stations since 1850 was reconstructed. The correlation coefficient between the change in snowfall day and annual temperature from 1951 to 2007 is −0.48, passing the 0.001 level of significance.

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2.2.3 Tree-ring data

Five tree-ring width chronologies (Table 1) derived from recent publications were used in this study (Duan et al., 2012; Zheng et al., 2012; Cao et al., 2012; Shi et al., 2013; Cai and Liu, 2013). The analysis of the relationship between tree growth and climate showed that the growth of trees in the study area was affected not only by the mean or minimum temperature in certain months (e.g., late winter to mid-summer) and maximum temperature in summer and early autumn, but also by the climatic conditions in the previous year. Here, we present the correlation coefficients (Table 1) to test whether these chronologies include the regional temperature signal. The results showed that all chronologies are significantly correlated with annual regional temperature changes, and most of the correlation coefficients between changes in tree-ring width and annual regional temperature of the previous year are also statistically significant.

2.3 Reconstruction and analysis methods

We applied stepwise regression to develop the calibration equation, in which the regional temperature anomaly (T) is the dependent variable, and the independent variables are phenodate (P), snowfall days (S), and five tree-ring width chronologies in both the current year and in the following year (i.e., $X_1, X_1(t+1), \ldots, X_5, X_5(t+1)$). The leave-one-out cross-validation method (Torrence and Compo, 1998) was then adopted for the verification in order to select the optimal equation with the highest predicted R^2 value for reconstruction. Because data for some years are missing in the series of spring phenodate anomaly and snowfall days, and two of the five tree-ring width chronologies did not extend back to 1850, the regression equation (Table 2) was constructed based on the available proxy data. For example, to reconstruct the temperature anomaly for 66 years when all seven proxy data are available, the stepwise regression was conducted based on all independent variables to perform the calibration equation (Eq. 1 in Table 2). The stepwise regression was conducted based on only the independent variables $S, X_1, X_1(t+1), \ldots, X_5, X_5(t+1)$ to construct the calibration equation

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(Eq. 2 in Table 2) for the temperature anomaly reconstruction when all proxy data but phenological data were unavailable. Table 2 shows that the predicted R^2 values of all calibration equations exceed 50 %, ranging from 56 to 66 %. This suggested that all calibration equations were valid for reconstruction.

Finally, the full series was constructed by merging the reconstructions for individual periods. Because the reconstructions for specific years were calibrated from different equations with different explained variances and predicted sums of squares, the magnitude of the reconstructed temperature for specific years had to be adjusted using variance matching with the standard deviations of the predictands in common years during the calibration period. For example, the standard deviations of the predictand series in common years of 1952 ~ 2006 (excluding 1997 and 1998 because of the lack of snowfall data) derived from Eqs. (1) and (2) are 0.35 (s1) and 0.42 (s2), respectively; thus, the reconstructed temperature anomalies in 1903 and 1904 derived from Eq. (2) should be adjusted by dividing by the value of s2/s1.

Moreover, wavelet analysis (Torrence and Compo, 1998) and the Mann–Kendall test (Wei, 2007) were applied to detect the cycle, trend and abrupt change for the reconstructed series of annual temperature anomaly in South Central China from 1850 to 2008.

3 Results and discussion

Figure 2 shows the reconstructed series of annual temperature anomaly and its 95 % confidence interval in South Central China from 1850 to 2008 along with a comparison between the reconstructed and observed temperatures from 1951 to 2007. The figure indicates that the temperature change in South Central China in the past 150 years was characterized by inter-annual and inter-decadal fluctuations before the 1980s and warming after the 1990s; the maximum amplitudes were 1.6 °C for inter-annual and 0.8 °C for inter-decadal variations. Quasi-15-year and quasi-35-year cycles were detected by wavelet analysis (Fig. 3a). The warm decades occurred in the 1850s,

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1870s and 1960s as well as during the 1920s ~ 1940s; the warmest decades were the 1990s ~ 2000s, which included 9 of the 10 warmest years from 1850–2008. Although the warm interval of the 1920s ~ 1940s persisted for more than 20 years, the level of warmth was notably lower than in the 1990s ~ 2000s. Cold intervals occurred in the 1860s, 1890s and 1950s, with slightly colder years occurring in the 1970s and 1980s. The Mann–Kendall test (Fig. 3b) showed that except for the notable cooling in the 1860s, the temperature fluctuated without any evident trend from the 1870s to the 1980s. However, significant warming has occurred since the 1990s with an abrupt change around 1997, which caused the unprecedented variability in warming.

The results also confirmed that 1893 was the coldest year during the period of 1850–2008; this same result has been found at most sites in China in previous studies (Gong et al., 1987; Hao et al., 2011; Zhang and Liang, 2014) in which many records on cold climate conditions were described in historical documents. For example, after a series of strong cold waves hit China in the winter of 1892 large-scale rain, snow and freezing weather phenomena occurred in South Central China; severe sea ice occurred in the coastal areas of northern Jiangsu Province (approximately 32–35° N), and the thickness of ice cover on Taihu Lake (approximately 30.9–31.6° N, 119.9–120.6° E) reached more than one foot (Gong et al., 1987). Historical documents indicate that the Huangpu and Wusong Rivers in Shanghai occasionally froze in the winter, with the ice not breaking up for more than ten days during Little Ice Age (LIA). Even the Qiantang River froze in the winter of 1892; historical documents indicate that this river has only frozen three times during the past 2000 years (the other two freezes occurred in the winters of 1152 and 1690) (Hao et al., 2011). Moreover, "the Diary of Zhang Jian" reported that *Prunus mume* was not in full blossom in Suzhou (east of China, 31.1° N, 120.6° E) until 21 March 1893, due to the extreme cold in the winter and early spring, which was delayed by 27 days compared to the mean of 1977–1996 (Zheng et al., 2013). In "the Diary of Xiangqi-Lou," the author Wang Kaiyun recorded, "*on the 7th day in the second lunar month (24 March, 1893) in Hengyang, Hunan Province, Prunus persica began to blossom. The phenodate in this spring was the latest one in my all records.*"

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He also commented, *"Ming-Tang-Yue-Ling [a book on natural phenological calendar by monthly before Han Dynasty] recorded that the first flowering of Prunus persica was usually on the solar terms [Chinese phenological calendar, having 24 points in one year and 15-days spaces at each point] of 'rain water' (18 to 20 February), while the people of Han Dynasty (202BC –AD220) recorded that it was usually on the solar terms of 'the insects awaken' (5 to 7 March). It was impossible to compare with the phenodates during recent years, because the early phenodate in spring was resulted from the warm climate, was the climate so warm in Han Dynasty and before? In last year, the swallows arrived here on the solar terms of 'the vernal equinox' (20 March), but this year, the solar terms of 'the tomb-sweeping' day (4 April) was coming soon, it was still as cold as winter ......"* (Wang, 1997). These comments indicated that the delayed spring phenophase in 1893 was extreme surpassed to what the authors were accustomed.

Comparing the reconstructed series with the observed temperature series (Fig. 2c) from Wuhan since 1906 (Cao et al., 2013) demonstrated that the reconstruction matched well with the observed data, especially in the decadal variations. The reconstructed and observed data both showed a warm interval of greater than 20 years during the 1920s ~ 1940s, an evident cold decade around 1950, and unprecedented warming beginning in the 1990s. However, the temperature change in South Central China was different from that in the Northern Hemisphere (Fig. 2d). The warm interval in the 1920s ~ 1940s indicated by both the reconstructed and observed data for South Central China was more evident than that found in the Northern Hemisphere. Specifically, the temperature in the Northern Hemisphere exhibited an increasing trend with a rate of 0.85 °C $(100\,a)^{-1}$ from 1880–2012, whereas the rate of increase in South Central China was only 0.28 °C $(100\,a)^{-1}$ from 1880–2008. This might be partly attributed to the difference in temperature change between regional and hemisphere scales; the rate of temperature increase in Wuhan was only 0.52 °C $(100\,a)^{-1}$ from 1906–2010, 50 % lower than the rate in the Northern Hemisphere (1.06 °C $(100\,a)^{-1}$).

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However, uncertainties were still presented in our reconstruction. These uncertainties might arise from the following factors: the phenological and snowfall data were missing in some years, and the temperature anomalies in these years (a total of 33 years) could only be reconstructed by using tree-ring width data. As pointed out by many studies (see the review paper of Yang et al., 2011), the tree-ring width data hardly captured the signal of low frequency trend signal due to growth de-trending. In addition, the reconstructions from all of the proxies only explained part of the temperature variability. Thus, our reconstruction may underestimate the increasing trend of temperature change. These shortcomings will be improved in future studies when more proxy data are available.

Compared with using one type of proxy (e.g., tree-ring width or historical cold/warm event records) to reconstruct regional temperature changes, our reconstruction has the advantage of utilizing multiple proxies (i.e., phenological, snowfall and tree-ring data), which can capture more information and reduce the uncertainty in the result. For example, a comparison of our reconstruction with previous seasonal temperature reconstructions using single tree-ring width (Duan et al., 2012; Cao et al., 2012; Shi et al., 2013; Cai and Liu, 2013) or snowfall day records (Hao et al., 2012), our annual temperature series has a higher explaining variance (more than 56 %) on temperature observation. The main reason for this might be that the phenological phenomena changes were highly sensitive to winter-spring temperature. Tree-ring width data from highlands in this area are sensitive to spring-summer minimum and mean temperature (i.e., positively correlated) (Duan et al., 2012; Zheng et al., 2012; Shi et al., 2013); however, the data from lower lands are negatively correlated to late-summer and early-autumn maximum temperature (Cai and Liu, 2013). The snowfall in this area is strongly correlated to winter temperature (Hao et al., 2012). Moreover, compared to annual temperature reconstruction in this area from 1880 (Wang et al., 1998), our reconstruction is extended to 1850, and the accuracy is improved, with a maximum error bar of only 0.35 °C at the 95 % confidence level.

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4 Conclusion

We presented a new annual temperature reconstruction with a maximum error of 0.35 °C at the 95 % confidence level in South Central China from 1850–2008 by synthesizing phenological, snowfall and tree-ring data. The accuracy of the reconstruction was improved by using multiple proxy types compared to using a single type of proxy. The results suggest that the temperature change in South Central China during the past 150 years was characterized by inter-annual and inter-decadal fluctuations before the 1980s, with a maximal amplitude of 1.6 °C for inter-annual and 0.8 °C for inter-decadal variations. Quasi-15-year and quasi-35-year interdecadal cycles were also detected, although rapid warming has occurred since the 1990s, with an abrupt change around 1997, leading to the unprecedented variability in warming. A cold interval dominated the 1860s, 1890s and 1950s, with slightly cold intervals around 1970 and in the 1980s. The coldest year overall was 1893. Warm decades occurred around 1850, 1870 and 1960 along with the 1920s ~ 1940s. The warmest decades were the 1990s ~ 2000s, which included 9 of the 10 warmest years from 1850–2008. However, our reconstruction may underestimate the increasing trend in temperature, this factor should be improved in future studies when more proxy data are available.

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Table 1. Basic information for five tree-ring width chronologies in or near the study area and the correlation coefficients (r) between tree-ring widths and annual regional temperature changes for the period of 1951–2007.

No.	Tree-ring width Chronology	Location	Duration	r	$r(t+1)^{a}$
X_1	Regional standard chronology of *Pinus masson*[25]	25 ~ 29° N, 111–115° E, 500 ~ 1450 m	1849 ~ 2008	0.608^{c}	0.192
X_2	*Pinus Taiwanese's Hayata* in Dabie Mountains[26]	31.1–31.2° N, 115.7–115.8° E, 1500 m	1883 ~ 2009	0.569^{c}	0.454^{c}
X_3	Taiwan pine in Dabie Mountains [27]	31.1° N, 116.2° E, 1640 ~ 1760 m	1834 ~ 2011	0.593^{c}	0.596^{c}
X_4	*Pinus massoniana Lamb* in Macheng County[28]	31.4° N, 115.2° E, 500 ~ 540 m	1895 ~ 2011	-0.377^{b}	-0.372^{b}
X_5	*Abies ziyuanensi* in Yanling County [29]	26.3–26.4° N, 114.0–114.1° E, 1530 m	1840 ~ 2010	0.425^{c}	0.367^{b}

[a] $r(t+1)$ is correlation coefficient between tree-ring width of current year and temperature of the previous year.
Significance level: [b] indicates $p < 0.01$; [c] indicates $p < 0.001$.

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Table 2. The calibration equations constructed by stepwise regression using the leave-one-out cross-validation method along with their adjusted $R^2(R^2_{adj})$ and predicted $R^2(R^2_{pr})$ values for annual temperature reconstruction in South Central China from 1850 to 2008.

Equation	Calibration equation	Regression	Years of reconstruction	R^2_{adj}	R^2_{pr}
1	$T = -0.055 - 0.046P - 0.087S + 0.123X_1 + 0.106X_2 - 0.078X_2(t+1) + 0.149X_3(t+1) - 0.107X_4$	P, S TR	1895 ~ 1910 (ex. 1903, 1904, 1907); 1952 ~ 2006 (ex. 1997, 1998)	0.72	0.66
2	$T = -0.056 - 0.109S + 0.137X_1 + 0.150X2 - 0.108X_2(t+1) - 0.092X_3 + 0.222X_3(t+1) - 0.103X_4$	S, TR	1903, 1904	0.70	0.63
3	$T = -0.037 - 0.098P + 0.134X_1 + 0.072X_2 + 0.147X_3(t+1) - 0.096X_4$	P, TR	1907, 1911 ~ 1916, 1947 ~ 1951, 1997 ~ 1998, 2007 ~ 2008	0.67	0.62
4	$T = -0.033 + 0.161X_1 + 0.117X_2 - 0.089X_2(t+1) + 0.208X_3(t+1) - 0.098X_4$	TR only	1917 ~ 1946	0.65	0.61
5	$T = -0.049 - 0.034P - 0.101S + 0.144X_1 + 0.069X_2 + 0.146X_3(t+1)$	All proxies except TR of X_4	1883, 1888 ~ 1894	0.65	0.60
6	$T = -0.043 - 0.111S + 0.138X_1 + 0.073X_2 + 0.142X_3(t+1)$	S, TR except X_4	1885 ~ 1887	0.65	0.59
7	$T = -0.037 - 0.092P + 0.133X_1 + 0.073X_2 + 0.165X_3(t+1) + 0.060X_5(t+1)$	P, TR except X_4	1884	0.65	0.59
8	$T = -0.044 - 0.037P - 0.113S + 0.174X_1 + 0.174X_3(t+1)$	Allproxies except X_2, X_4	1862,1868, 1874, 1878	0.63	0.59
9	$T = -0.036 - 0.125S + 0.170X_1 + 0.172X_3(t+1)$	S, TR except X_2, X_4	1850 ~ 1881 ex. 1860, 1862, 1864, 1868, 1871, 1874, 1876, 1878	0.63	0.59
10	$T = -0.030 - 0.094P + 0.162X_1 + 0.191X_3(t+1) + 0.061X_5(t+1)$	P, TR except X_2, X_4	1864, 1882	0.63	0.58
11	$T = -0.022 + 0.181X_1 + 0.208X_3(t+1) + 0.062X_5$	TR except X_2, X_4	1860, 1871, 1876	0.60	0.56

P means phenological data, S means snowfall days and TR means all tree-ring chronology data.

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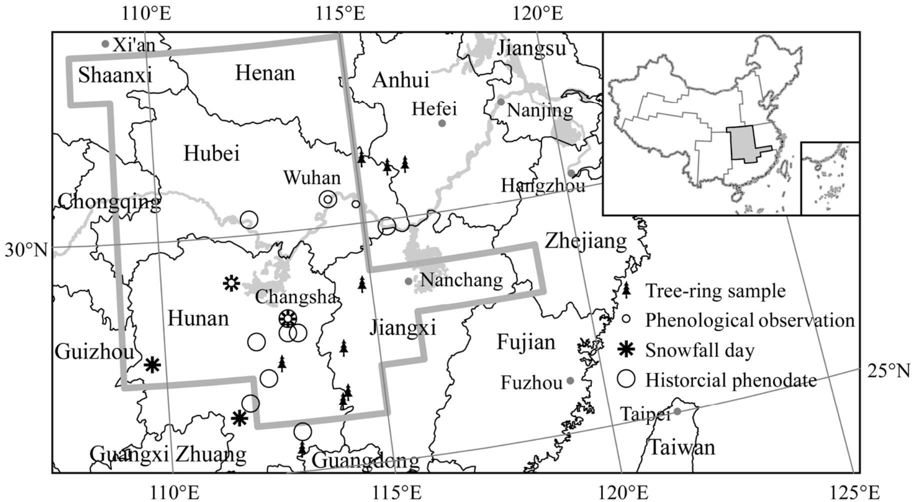

Figure 1. The study area and locations of proxy data used for annual temperature reconstruction in South Central China. Top right: sub-regions divided by the climate regionalization and the coherences of temperature change (cited from Wang et al., 1998). The gray area indicates South Central China.

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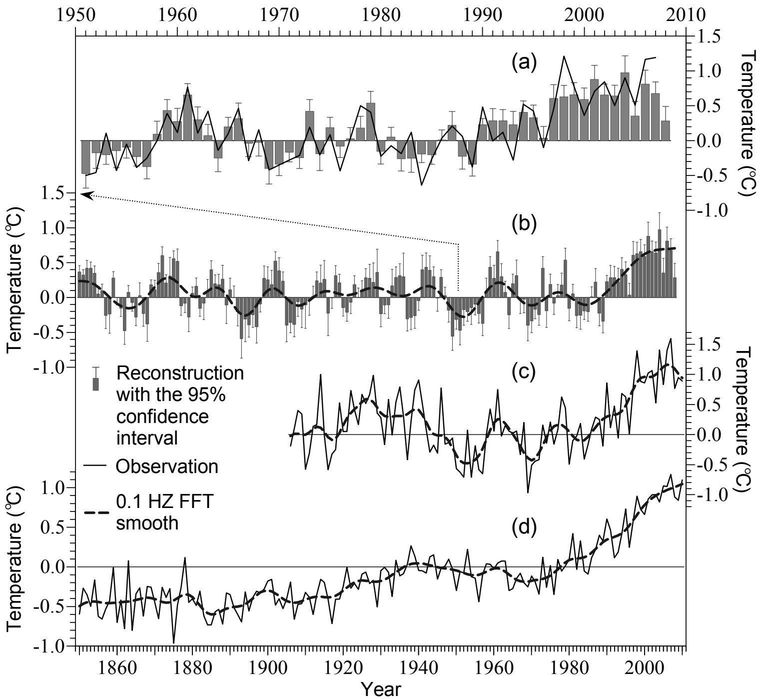

Figure 2. Reconstruction of annual temperature anomalies (with respect to the mean climatology from 1961 to 1990, as for other series) based on a 95 % confidence interval in South Central China from 1850 to 2008 and comparison with observations. **(a)** Comparison between the reconstructed and observed temperature anomalies in South Central China from 1951 to 2007; **(b)** reconstructed annual temperature anomalies in Central China during 1850–2008; **(c)** observed annual temperature anomalies at the Wuhan weather station during 1906–2010; **(d)** Northern Hemisphere land air temperature anomalies during 1850–2010 from CRU (Climatic Research Unit, http://www.cru.uea.ac.uk/cru/data/temperature/CRUTEM4v-nh.dat).

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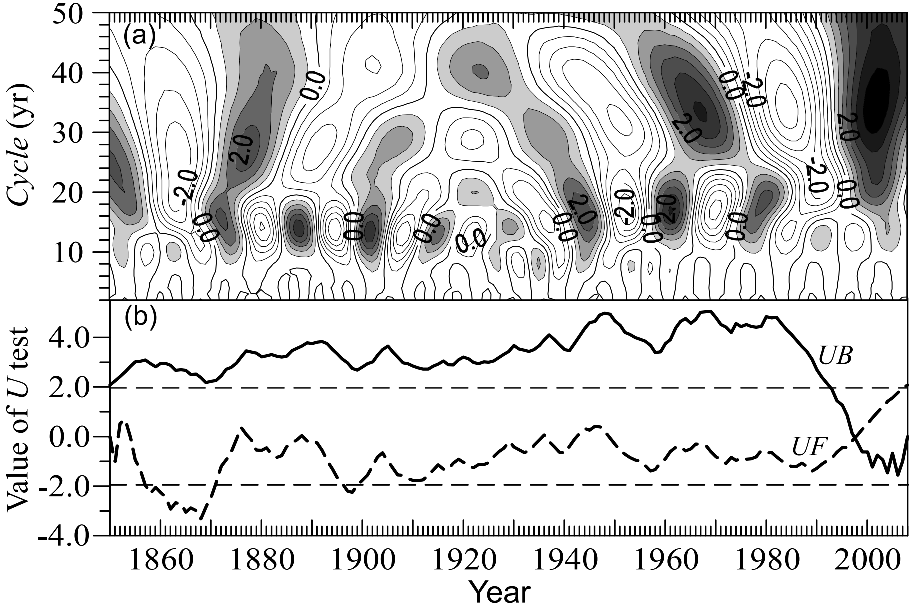

Figure 3. Results of wavelet analysis **(a)** and Mann–Kendall test **(b)** for annual temperature series in South Central China from 1850 to 2008.

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