Clim. Past, 9, 1153–1160, 2013
www.clim-past.net/9/1153/2013/
doi:10.5194/cp-9-1153-2013

Climate of the Past
Open Access

Temperature changes over the past 2000 yr in China and comparison with the Northern Hemisphere

Q. Ge, Z. Hao, J. Zheng, and X. Shao

Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

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

Received: 12 December 2012 – Published in Clim. Past Discuss.: 24 January 2013
Revised: 23 April 2013 – Accepted: 2 May 2013 – Published: 27 May 2013

Abstract. We use principal component regression and partial least squares regression to separately reconstruct a composite series of temperature variations in China, and associated uncertainties, at a decadal resolution over the past 2000 yr. The reconstruction is developed using proxy temperature data with relatively high confidence levels from five regions across China, and using a temperature series from observations by the Chinese Meteorological Administration, covering the period from 1871 to 2000. Relative to the 1851–1950 climatology, our two reconstructions show four warm intervals during AD 1–AD 200, AD 551–AD 760, AD 951–AD 1320, and after AD 1921, and four cold intervals during AD 201–AD 350, AD 441–AD 530, AD 781–AD 950, and AD 1321–AD 1920. The temperatures during AD 981–AD 1100 and AD 1201–AD 1270 are comparable to those of the Present Warm Period, but have an uncertainty of ±0.28 °C to ±0.42 °C at the 95 % confidence interval. Temperature variations over China are typically in phase with those of the Northern Hemisphere (NH) after 1000, a period which covers the Medieval Climate Anomaly, the Little Ice Age, and the Present Warm Period. In contrast, a warm period in China during AD 541–AD 740 is not obviously seen in the NH.

1 Introduction

The use of multiple types of proxy data to reconstruct temperature records covering the past few millennia over large geographic regions is a relatively new area of scientific research (National Research Council, 2006). Regional reconstructions that increase the spatial coverage of individual datasets would be a major step towards the development of a more accurate dataset (PAGES, 2009) that would reduce the uncertainties associated with current reconstructions and contribute to our understanding of the spatial patterns of global temperature changes (Mann et al., 2009). Consequently, the Past Global Changes (PAGES) project established nine regional working groups to form a collaborative global network that aims to synthesize data on climate variability over the past 2000 yr. At the Asia2k workshop held in Thailand on 9–12 January 2012, paleoclimate scientists were assigned the task of reconstructing a time series of temperature changes over China during the past 2000 yr. The results will contribute to the meaningful analysis of temperature change in the Northern Hemisphere (NH), and to a better understanding of geographical differences between neighboring regions in Asia.

Since the 1970s, scientists have reconstructed a number of time series showing surface temperature variations in China over the past two millennia using natural proxies, such as tree rings, ice cores, lake sediments, stalagmites, as well as archaeological evidence and historical documents (Chu, 1973; Shao and Wu, 1994; Yao et al., 1996; Zhang, 1996). Based on these proxies, Yang et al. (2002) and Wang et al. (2007) presented two composite temperature reconstructions covering the whole of China for the past 2000 yr. However, the limited availability of temperature proxies and reconstruction approaches led to differences in climate variability between the two reconstructions. In recent decades, many reconstructions have been attempted at individual sites, or over small areas, based on natural proxies. These new reconstructions allow proxy records to be updated, and provide the opportunity to reappraise previous reconstructions of past temperatures in China using the enlarged proxy dataset and employing new spatial and temporal statistical techniques. Thus, Shi

Published by Copernicus Publications on behalf of the European Geosciences Union.

et al. (2012) presented a millennial-scale gridded field reconstruction of annual temperature over China based on the statistical techniques of composite plus scaling and regularized errors-in-variables, and Cook et al. (2013) used tree-ring data from various sites to reconstruct the annual temperature in East Asia from AD 800 to AD 1989.

The uncertainties associated with the reconstructed temperature record for China over the past 2000 yr have been evaluated (Ge et al., 2010), and coherent temperature records from five regions (Northeast, Central East, Southeast, and Northwest China, and the Tibet Plateau) have been developed (Fig. 1). Here, we use principal component regression (PCR) and partial least squares (PLS) regression to separately reconstruct temperature changes over the whole of China based on these five coherent series, and we then consider the differences between the two reconstructions. Compared with previous long-term temperature reconstructions for China, our new contribution is that the characteristics of regional climate are considered, and that the uncertainties of all the original temperature proxies have been evaluated, thereby enabling the construction of regional temperature curves with high levels of confidence. In addition, we compare the temperature record for China at a centennial timescale with that of the NH, paying particular attention to the Medieval Climate Anomaly (MCA), the Little Ice Age (LIA), and the Present Warm Period (PWP). We identify differences and similarities between the patterns of temperature change seen in China and the NH.

2 Data and methods

Ge et al. (2010) divided China into five regions based on geographic location and temperature characteristics from 1961 to 2007 (Northeast, NE; Central East, CE; Southeast, SE; Northwest, NW; and the Tibet Plateau, TP), and systematically evaluated the similarities and differences among the regions in terms of temperature change over the past 2000 yr (Fig. 1). In the present study, the temperature in China over the past 2000 yr is reconstructed from temperature anomalies with respect to the 1851–1950 climatology, at a decadal resolution. Specifically, in the NE region the temperature is reconstructed from AD 1 to AD 1990, in CE from AD 1 to AD 2000, in SE from AD 1471 to AD 1950, in NW from AD 851 to AD 2000, and in TB from AD 1 to AD 2000. Table 1 lists the original temperature proxies from various studies, including the proxy type, location of the study site, season of measurement, the period of reconstruction, time resolution, the explained variance of the regional observations, and references. The locations of the study sites are indicated in Fig. 1. Among them, data from NE and SE are extended to 2000 based on records of warm/cold periods in historical documents (Hao et al., 2011). In TP and NW, some of the original temperature proxies have been updated (in TP: Thompson et al., 2000, 2003, 2006; Shen et al., 2001; Liu et al., 2006; Wang et al., 2006; Zhu et al., 2008; in NW: Liu et al., 2005; Zhang et al., 2011), and we were able to re-evaluate the records of temperature change in these two regions using the method of Ge et al. (2010). The decadal temperature time series extends from 1 to 2000 in CE, TP and NE; from 851 to 2000 in NW; and from 1471 to 2000 in SE. As the start point of the records varied among the regions, the temperature record for the whole of China is reconstructed for three periods based on the available datasets; i.e., TP, CE, and NE are used for the period from 1 to 850; TP, CE, NE, and NW from 851 to 1470; and all five regions from 1471 to 2000.

The annual temperature changes from 1871 to 2000 are obtained from observations by the Chinese Meteorological Administration (Lin et al., 1995; updated in Tang et al., 2009). This dataset contains the mean temperature for 10 subregions in China, derived from data from 711 stations, including 165 stations for which data are available for the entire period, 165 stations for which data are available after 1951, and 381 stations for which data are available prior to 1951 (Lin et al., 1995). The mean decadal values from this dataset, for the period between 1871 and 2000, are used to develop the reconstruction models and to calibrate and verify the temperatures.

We reconstruct the temperature time series using the PLS and PCR approaches, which are the two most commonly used methods for biased regression analysis. PLS usually requires fewer components and gives a lower prediction error than PCR, and has been recommended for the quantitative reconstruction of paleoenvironmental data (Birks, 1995). The optimal (selected) number of PLS components is estimated by leave-one-out cross-validation (Michaelsen, 1987) on the basis of a low prediction error sum of squares and high predicted R^2. We use MINITAB to perform the PLS and PCR analyses (Meyer and Krueger, 2004), and the results are listed in Table 2. The predictors are the reconstructed temperature series from the five regions at a decadal time resolution (following Ge et al., 2010). The predictand for the model fitting from 1871 to 2000 is the mean decadal temperature for China calculated by the CMA. For the PCR method, the first two components are selected to build the regression models, and their cumulative contribution rate of variance is 76 % during the period 1–850, 70 % during 851–1470, and 71 % during 1471–2000. To resolve the problem of inhomogeneity among the reconstructions caused by the variable number of predictors analyzed, we calibrate the temperature mean value and variance to the same level in the common period from 1471 to 2000. For example, during the period 1–850, time series for only three regions (NE, CE, and TB) can be used to reconstruct the temperature. To maintain the homogeneity of the reconstructed series, we also use these three series and all five series to separately reconstruct the temperature for the period 1471–2000, and we then compare the mean values and variances for the two sets of results. If the mean value obtained from the three regional series is higher (lower) than that from the five regional series, we then subtract (add)

Table 1. Records of the reconstructed temperature proxies shown in Fig. 1 (proxy types: SD, sediments; ST, stalagmites; HD, historical documents; TR, tree rings; IC, ice cores).

Proxy type	Coordinate	Measurement interpretation	Reconstructed period	Resolution	Explained variance	Reference
			Northeast			
SD	Jinchuan peat (42.33° N, 126.37° E)	δ^{18}O ‰, annual average temperature	3965 BC–1950 AD	10–100 a	15 %	Hong et al. (2000)
SD	Lake Sihailongwan (42.28° N, 126.60° E)	Long-chain alkenone, growing season	350–1990 AD	10–30 a	14 %	Chu et al. (2012)
ST	Shihua cave (39.80° N, 115.80° E)	Stalagmite microlayer thickness, May–August temperature	665 BC–1985 AD	1 a	37 %	Tan et al. (2003)
HD	Shandong Province (36.63° N, 117.00° E)	Cold/warm year counts for every ten years, winter temperature	1470s–1980s	10 a	77 %	Zheng and Zheng (1993)
HD	North China (40.00° N, 118.00° E)	Cold/warm description, annual temperature	1380s–1990s	10 a	40 %	Wang et al. (1998)
			Northwest			
TR	Central part of Qilian Mountain (north face) (38.83° N, 99.62° E)	Qilian juniper ring width, annual minimum temperature	850–2000	1 a	13 %	Zhang et al. (2011)
TR	Central part of Qilian Mountain (north face) (38.43° N, 99.93° E)	Qilian juniper ring width, December–April temperature	900–2000	1 a	22 %	Liu et al. (2005), updated
			Central East			
HD	East China (25–40° N, east of 105° E)	Phenophase, winter-half-year temperature	1–2000	10–30 a	71 %	Ge et al. (2003)
HD	East China (25–35° N, 115–120° E)	Winter cold index, winter temperature	1470s–1970s	10 a	81 %	Wang and Wang (1990)
HD	Taihu Lake (31.50° N, 120.50° E)	Severe/cold/hot/warm winter years count, winter temperature	1380s–1970s	10a	25 %	Shen and Chen (1991)
HD	Lower reaches of the Yangtze River (32.10° N, 118.80° E)	Frequency of cold/warm years, winter temperature	1470s–1960s	10 a	16 %	Zhang (1980)
HD	Middle reaches of the Yangtze River (30.50° N, 114.50° E)	Same as above	1470s–1960s	10 a	50 %	Zhang (1980)
HD	Hunan-Jiangxi (28.00° N, 116.50° E)	Same as above	1470s–1960s	10 a	10 %	Zhang (1980)
HD	East China region (34.00° N, 120.00° E)	Cold/warm descriptions, annual temperature	1380s–1990s	10 a	49 %	Wang et al. (1998)
HD	Central China (29.00° N, 113.00° E)	Same as above	1470s–1990s	10 a	73 %	Wang et al. (1998)
			Tibet Plateau			
IC	Dasuopu (28.38° N, 85.72° E)	δ^{18}O ‰, annual temperature	1000–2000	10 a	51 %	Thompson et al. (2000)
IC	Dunde (38.1° N, 96.4° E)	δ^{18}O ‰, annual temperature	1000–1980	10 a	55 %	Thompson et al. (2003)
IC	Guliya (37.19° N, 80.68° E)	δ^{18}O ‰, annual temperature	1000–1990	10 a	25 %	Thompson et al. (2003)
IC	Puruogangri (33.92° N, 89.08° E)	δ^{18}O ‰, annual temperature	1–1990	10 a	5 %	Thompson et al. (2006)
IC	Malan (35.83° N, 90.67° N)	δ^{18}O ‰, annual temperature	1130–1990	10 a	6 %	Wang et al. (2006)
TR	Wulan Qinghai Province (37.05° N, 98.67° N)	Qilian juniper ring width, September–April temperature	1000–2004	1 a	35 %	Zhu et al. (2008), updated
SD	Qinghai Lake (36.60° N, 100.50° E)	Total Organic Carbon (TOC), annual temperature	1050–2000	20 a	1 %	Shen et al. (2001)
SD	Qinghai Lake (37° N, 100° E)	Alkenone, summer lake water temperature	1500 BC–2000 AD	30–100 a	8 %	Liu et al. (2006)
			Southeast			
HD	Guangdong and Guangxi provinces (23.50° N, 112.50° E)	Frequency of cold/warm years, winter temperature	1470s–1960s	10 a	63 %	Zhang (1980)
HD	Zhejiang and Fujian provinces (25.00° N, 118.00° E)	Same as above	1470s–1960s	10 a	43 %	Zhang (1980)
HD	Guangdong (23.16° N, 113.23° E)	Cold winter record pieces in every ten years, winter temperature	1400s–1940s	10a	8 %	Zheng (1982)
HD	Fujian and Taiwan (24.00° N, 121.00° E)	Cold/warm description, annual temperature	1500s–1990s	10 a	2 %	Wang et al. (1998)
HD	South China (23.00° N, 114.00° E)	Same as above	1500s–1990s	10 a	70 %	Wang et al. (1998)

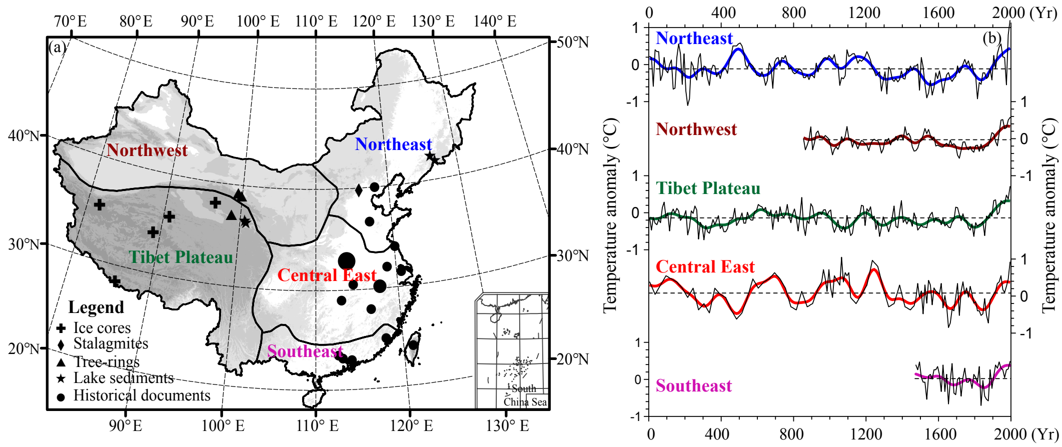

Fig. 1. Spatial distribution of the cited temperature proxy series **(a)** and temperature changes at a centennial timescale (5-point FFT filter) in five regions of China (Northeast, Central East, Southeast, Northwest, and the Tibet Plateau) (**b**). The temperature anomaly in the right-hand plot is the temperature departure from the 1851–1950 average. The decadal series are from Ge et al. (2010) and are updated for the Tibet Plateau and Northwest China. Dashed lines indicate the overall mean value for each temperature series.

Table 2. Selected number of components from the PLS regression and the first two components from the PCR between proxies and observations. Verifications are based on the leave-one-out cross-validation method.

Periods	Methods	Models[a]	Variances	SE[b]	PRESS[c]	Predicted R^2
1–850	PLS	1	0.76	0.60	0.88	0.42
		2*	0.92	0.39	0.77	0.49
		3		0.34	1.13	0.25
	PCR				0.95	0.37
851–1470	PLS	1	0.73	0.67	0.99	0.34
		2*	0.87	0.39	0.83	0.45
		3		0.34	1.20	0.21
		4		0.34	1.18	0.22
	PCR				0.63	0.58
1471–2000	PLS	1*	0.70	0.67	1.07	0.29
		2		0.44	1.10	0.27
		3		0.35	1.20	0.20
		4		0.30	1.65	0.00
		5		0.30	1.60	0.00
	PCR				1.18	0.21

[a] Asterisks indicate the model with the highest predicted R^2. [b] SE = standard error. [c] PRESS = prediction error sum of squares.

the difference in temperature for the period 1–850, and the variance is calibrated similarly.

3 Results

Figure 2 shows decadal temperature variations (with respect to the mean value for the period 1851–1950) and the centennial-scale temperature signal smoothed by a 5-point fast Fourier transform (FFT) filter for the past 2000 yr, along with 95 % confidence intervals, derived from the PCR and PLS analyses. Because the raw temperature proxies used here have a temporal resolution of 1–30 yr (Ge et al., 2010), it is more appropriate to consider variations in the temperature signal over a centennial timescale. Relative to the reference climatology from 1851 to 1950, the PCR reconstruction contains four warm intervals (1–200, 531–780, 951–1320, and 1921–2000) and three cold intervals (201–530, 781–950, and 1321–1920). The amplitude of the temperature change (difference between the minimum and maximum) for the whole series is 0.55 ± 0.16 °C (95 % confidence level). The two warm peaks that exceed the temperature of the 20th century climatology occurred during the periods 981–1100 and 1201–1270. The PLS centennial reconstruction shows five warm intervals (1–200, 351–440, 551–760, 951–1320, and 1921–2000) and four cold intervals (201–350, 441–550, 761–950, and 1321–1920). The amplitude of temperature variations during the past 2000 yr is 0.65 ± 0.13 °C. The 20th century is the third warmest interval in this period, with the warmest being 1201–1270 followed by 981–1100.

A comparison of the two reconstructions reveals consistent warming periods at 1–200, 551–760, 951–1320, and after 1921, and cooling periods at 201–350, 441–530, 781–950, and 1321–1920. The correlation coefficient between the two reconstructions is 0.86 for the decadal timescale, and 0.94 for the centennial FFT-filtered series, exceeding the 95 % confidence level. The temperature difference between the two reconstructions is less than 0.2 °C in 90 % of the decades (data points), and a difference greater than 0.2 °C is found for the decades during the periods 251–310 and 601–850. These results indicate that the reconstruction method and the predictive ability of the fitting model could affect the procedure used to calculate the temperature variations. For example, PCR is more sensitive to the common characteristics of the original proxies than to the extreme values, while PLS collects more information than PCR regarding temperature changes, and is better able to capture extreme signals. Thus, the predicted standard errors associated with the difference in

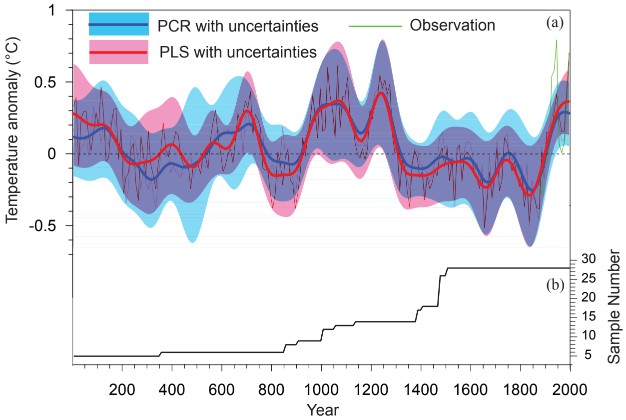

Fig. 2. (a) Ensemble temperature reconstructions based on PLS (red lines) and PCR (blue lines) methods at decadal (thin lines) and centennial timescales (solid lines; smoothed by a 5-point FFT filter), along with the 95 % confidence level (shading). The reference value is the mean temperature from 1851 to 1950. The green line indicates the observed average air temperature. **(b)** Numbers of samples used.

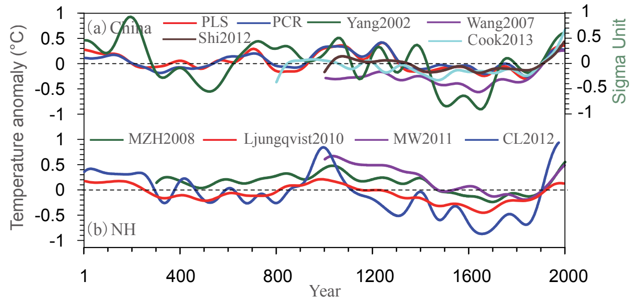

Fig. 3. Comparison of temperature reconstructions for China **(a)** and the Northern Hemisphere **(b)**. The reference period is from 1851 to 1950. The right-hand axis (marked "Sigma Unit") is for the Yang et al. (2002) series. All color lines have been smoothed using a 100 yr FFT filter.

temperature changes reconstructed by the two methods are high for some periods in which the original sources of the temperature data are inconsistent. In addition, PLS yields a higher variance explanation and has a higher variation amplitude than PCR, and this may help to overcome the problem of underestimating low-frequency variations, which is inherent in other reconstruction methods (e.g., Christiansen et al., 2009). Figure 2a shows that large uncertainties (departure from the mean by more than two standard deviations of the reconstructions) are mainly found for the periods 431–690, 1021–1090, 1231–1290, 1611–1670, and 1781–1850 for the PCR reconstruction, and for 1011–1110 and 1231–1290 for the PLS reconstruction. Considering the original temperature proxies (see Fig. 2b), the uncertainties in the reconstructions may reflect the small number of samples used for the period 431–690 or the high degree of inconsistency between the original series; e.g., the difference between the highest and lowest temperatures ranges from 0.62 °C to 1.56 °C for the period 1021–1100, and from 1.05 °C to 1.30 °C for the period 1231–1290.

4 Comparison with other reconstructions

We compared our composite temperature records with four series constructed previously for China and East Asia. Yang et al. (2002) developed three series of temperature variations (using the standard deviation rather than the temperature anomaly) based on nine separate temperature reconstructions (four from the Tibetan Plateau, two from eastern China, and three from outside of China) from multi-proxy records that were analyzed using three different statistical methods. Compared with Yang et al. (2002), our reconstruction used new temperature proxies, especially from eastern China, with a higher spatial resolution. Wang et al. (2007) divided China into 10 subregions based on regional observational climate and temperature changes. The temperature series for each subregion were reconstructed individually before the 10 series were combined to generate the temperature series for the entire country using area-weighted subregional temperature records. However, the important climate periods of the MCA (950s–1200s) and the LIA (15th to 19th centuries, varied depending on the different study; Matthews and Briffa, 2005; Miller et al., 2012) are not represented consistently by these two studies because of differences in the reconstruction methods and proxies used. Shi et al. (2012) reconstructed a 1000 yr record of annual temperature based on a network of 415 climatic proxy series, using a modified point-by-point regression; however, the low spatial and temporal resolutions of the original temperature proxies have a negative effect on the accuracy of the results. Cook et al. (2013) reconstructed summer temperature in East Asia from 800 to 1989 based on tree-ring data, mainly from West China.

Figure 3a shows the temperature anomalies (with respect to the mean climatology between 1851 and 1950) of the above studies, and the present study, smoothed by a 100 yr FFT filter. At the centennial timescale, the correlation coefficient between our PCR (or PLS) reconstruction and the reconstructions of Yang et al. (2002), Wang et al. (2007), Shi et al. (2012), and Cook et al. (2013) is 0.48 (0.47) for the period from 1 to 2000, 0.57 (0.51) from 1001 to 2000, 0.83 (0.79) from 1001 to 1990, and 0.56 (0.52) from 801 to 2000, respectively. All the correlation coefficients are statistically significant at the $\alpha = 0.01$ level. From 1401 to 2000, the four series from the previous studies show good agreement with each other, and all perform well in reproducing the cold phase of the LIA and the warming trend from the LIA to the PWP, despite the differences among the series in terms of the warming rate per century. Our reconstructions and Yang et al. (2002) show that for the past 2000 yr, the warm temperatures of the 20th century are not unprecedented, as similar temperatures occurred during 1001–1260, although the timing of the peak warm period varies among the reconstructions. The procedure employed in the present study to calculate temperature variations means that our reconstructions more clearly identified the warming peak during the MCA, compared with Wang et al. (2007) and Cook et al. (2013), and show an increased amplitude of temperature variations from 1001 to 2000.

We now compare the temperature variations between China and the Northern Hemisphere. Patterns of temperature variation and their associated uncertainty for most of the NH reconstructions were analyzed in a National Research Council report (NRC, 2006) and by IPCC AR4 (Jansen et al., 2007). Subsequently, some new NH reconstructions covering the past millennium have been published based on new or extended temperature series and new statistical reconstruction methods (Mann et al., 2008, 2009; Christiansen et al., 2009; Ljungqvist, 2010; Mcshane and Wyner, 2011; Christiansen and Ljungqvist, 2012; PAGES 2k Consortium, 2013). From these studies, we used four temperature series smoothed by a 100 yr FFT filter to compare with our PLS reconstructions, and we refer to them in Fig. 3 by the first letters of the authors' surnames and the year of publication, as follows: Mann et al. (2008, the EIV (errors-in-variables) land reconstruction), Ljungqvist (2010), Mcshane and Wyner (2011), and Christiansen and Ljungqvist (2012) (Fig. 3b). The PLS reconstruction shows strong correlations with Mann et al. (2008), Ljungqvist (2010), Mcshane and Wyner (2011), and Christiansen and Ljungqvist (2012) from the 11th century to the 20th century, with correlation coefficients of 0.81, 0.84, 0.83, and 0.68, respectively (significant at the $\alpha = 0.01$ level). This indicates that the temporal pattern of temperature change in China is consistent with that in the NH, and that in both regions the warming trend of the PWP started in the middle of the 19th century. Mcshane and Wyner (2011) and Ljungqvist (2010) show that temperatures during the MCA reached or exceeded those of the PWP. During the first millennium, the correlation coefficient with our reconstruction is 0.46 for Ljungqvist (2010), 0.41 for Christiansen and Ljungqvist (2012), and 0.23 for Mann et al. (2008) (significant at the $\alpha = 0.05$ level). For the period prior to AD 1000, the trends show a greater difference between China and the NH. For example, from 301 to 500, temperatures were increasing in China but decreasing in the NH, and from 701 to 850 temperatures were decreasing in China and increasing in the NH. Of note, a warm period in China from 541 to 740 is not recorded in the NH.

A comparison between our PLS reconstruction and a Mongolian temperature record inferred from the chronology of tree-ring widths in a Siberian Pine (D'Arrigo et al., 2001) shows a very close agreement after 1500 (i.e., both series show cold conditions in the 16th century, warm in the 18th century, cold in the 19th century, and warm in the 20th century). A comparison between the PLS reconstruction and springtime temperatures in Japan based on phenological data from the flowering of cherry trees in Kyoto (Aono and Kazui, 2008) shows the same extreme temperatures from the 9th century, including cold conditions in the 1650s and 1820s, and warm in the 12th and 20th centuries. Thus, regardless of how the time series were produced, all of the reconstructions show a spatially coherent period of LIA cooling from the beginning of the 16th century, and PWP warming during the 20th century within China, neighboring areas, and the NH.

5 Conclusions

The PCR and PLS temperature reconstructions for China over the past 2000 yr show warm intervals at AD 1–AD 200, AD 551–AD 760, AD 951–AD 1320, and after AD 1921, and cold intervals at AD 201–AD 350, AD 441–AD 530, AD 781–AD 950, and AD 1321–AD 1920. The warming during the 20th century is not unprecedented, as similar warming occurred during 981–1100 and 1201–1270, although the reconstructions for these intervals have uncertainties of ± 0.28 to ± 0.35 °C at the 95 % confidence level, respectively. The two coldest periods occurred during 1631–1690 and 1811–1870. The difference between the minimum temperature in the LIA and the maximum temperature in the PWP is 0.65 ± 0.13 °C in the PLS reconstruction, and 0.55 ± 0.16 °C in the PCR reconstruction on a centennial timescale. The rate of warming between 1851 and 1950 is 0.88 °C/100 yr in the PLS reconstruction and 0.92 °C/100 yr in the PCR reconstruction, and this period represents a transition from the LIA to PWP.

The variations in temperature during the MCA, LIA, and PWP in China are consistent with those in the NH. However, the warming in China during 541–740 was more pronounced than in the NH. The small number of samples, combined with inconsistencies in the original temperature proxies, means that the warm temperatures in 981–1100 and 1201–1270, which are comparable to the temperatures of the 20th century, have large uncertainties. Therefore, the accuracy of reconstructions needs to be improved for these periods, at least for East Asia.

Acknowledgements. This research was supported by grants to IGSNRR from the Ministry of Science and Technology of the People's Republic of China (2010CB950100), the Chinese Academy of Sciences (XDA05080100), Commonwealth research funding from CMA (GYHY201106013-2-2), and the National Natural Science Foundation of China (41071029).

Edited by: D. Fleitmann

References

Aono, Y. and Kazui, K.: Phenological data series of cherry tree flowering in Kyoto, Japan, and its application to reconstruction of springtime temperatures since the 9th century, Int. J. Climatol., 28, 905–914, 2008.

Birks, H. J. B.: Quantitative paleoenvironmental reconstruction, in: Statistical Modeling of Quaternary Science Data, edited by: Maddy, D. and Brew, J. S., Cambridge, UK, 161–254, 1995.

Christiansen, B. and Ljungqvist, F. C.: The extra-tropical Northern Hemisphere temperature in the last two millennia: reconstructions of low-frequency variability, Clim. Past, 8, 765–786, doi:10.5194/cp-8-765-2012, 2012.

Christiansen, B., Schmith, T., and Thejll, P.: A surrogate ensemble study of climate reconstruction methods: stochasticity and robustness, J. Climate, 22, 951–976, 2009.

Chu, G. Q., Sun, Q., Wang, X. H., Liu, M. M., Lin, Y., Xie, M. M., Shang, W. Y., and Liu, J. Q.: Seasonal temperature variability during the past 1600 years recorded in historical documents and varved lake sediment profiles from northeastern China, Holocene, 22, 785–792, 2012.

Chu, K.: A preliminary study on the climatic fluctuations during the last 5000 years in China, Sci. China Ser. A, 16, 226–256, 1973.

Cook, E. and PAGES Asian2k Members: Tree-ring reconstructed summer temperature anomalies for temperate East Asia since 800 C.E., Clim. Dynam., online first, doi:10.1007/s00382-012-1611-x, 2013.

D'Arrigo, R., Jacoby, G., Frank, D., Pederson, N., Cook, E., Buckley, B., Nachin, B., Mijiddorj, R., and Dugarjav, C.: 1738 years of Mongolian temperature variability inferred from a tree-ring width chronology of Siberian Pine, Geophys. Res. Lett., 28, 543–546, 2001.

Ge, Q. S., Zheng, J. Y., Fang, X. Q., Man, Z. M., Zhang, X. Q., Zhang, P. Y., and Wang, W. C.: Winter half-year temperature reconstruction for the middle and lower reaches of the Yellow River and Yangtze River, China, during the past 2000 years, Holocene, 13, 933–940, 2003.

Ge, Q. S., Zheng, J. Y., Hao, Z. X., Shao, X. M., Wang, W. C., and Luterbacher, J.: Temperature variation through 2000 years in China: An uncertainty analysis of reconstruction and regional difference, Geophys. Res. Lett., 37, L03703, doi:10.1029/2009GL041281, 2010.

Hao, Z. X., Zheng, J. Y., and Ge, Q. S.: Historical analogues of the 2008 extreme snow event over Central and Southern China, Clim. Res., 50, 161–170, doi:10.3354/cr01052, 2011.

Hong, Y. T., Jiang, H. B., Liu, T. S., Zhou, L. P., Beer, J., Li, H. D., Leng, X. T., Hong, B., and Qin, X. G.: Response of climate to solar forcing recorded in a 6000-year δ^{18}O time-series of Chinese peat cellulose, Holocene, 10, 1–7, 2000.

Jansen, E., Overpeck, J., Briffa, K. R., Duplessy, J.-C., Joos, F., Masson-Delmotte, V., Olago, D., Otto-Bliesner, B., Peltier, W. R., Rahmstorf, S., Ramesh, R., Raynaud, D., Rind, D., Solomina, O., Villalba, R., and Zhang, D.: Palaeoclimate, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge and New York, 2007.

Lin, X. C., Yu, S. Q., and Tang, G. L.: Series of average air temperature over China for the last 100-year period, Scientia Atmospherica Sinica, 19, 525–534, 1995.

Liu, X. H., Qin, D. H., Shao, X. M., Chen, T., and Ren, J. W.: Temperature variations recovered from tree-rings in the middle Qilian Mountain over the last millennium, Sci. China Ser. D, 48, 521–529, 2005.

Liu, Z. H., Henderson, A. C. G., and Huang, Y. S.: Alkenone-based reconstruction of late-Holocene surface temperature and salinity changes in Lake Qinghai, China, Geophys. Res. Lett., 33, L09707, doi:10.1029/2006GL026151, 2006.

Ljungqvist, F. C.: A new reconstruction of temperature variability in the extra-tropical Northern Hemisphere during the last two millennia, Geogr. Ann. A, 92, 339–351, 2010.

Mann, M. E., Zhang, Z., Hughes, M. K., Bradley, R. S., Miller, S. K., Rutherford, S., and Ni, F. B.: Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia, P. Natl. Acad. Sci., 105, 13252–13257, 2008.

Mann, M. E., Zhang, Z., Rutherford, S., Bradley, R. S., Hughes, M. K., Shindell, D., Ammann, C., Faluvegi, G., and Ni, F.: Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly, Science, 326, 1256–1260, 2009.

Matthews, J. A. and Briffa, K. R.: The "Little Ice Age": reevaluation of an evolving concept, Geogr. Ann., 87A, 17–36, 2005.

Mcshane, B. B. and Wyner, A. J.: A statistical analysis of multiple temperature proxies: Are reconstructions of surface temperatures over the last 1000 years reliable?, Ann. Appl. Stat., 5, 5–44, 2011.

Meyer, R. K. and Krueger, D. D.: A Minitab Guide to Statistics, 3rd Edn., NJ, Prentice-Hall Publishing, 448 pp., 2004.

Michaelsen, J.: Cross-validation in statistical climate forecast models, J. Clim. Appl. Meteorol., 26, 1589–1600, 1987.

Miller, G. H., Geirsdóttir, Á., Zhong, Y. F., Larsen, D. J., Otto-Bliesner, B. L., Holland, M. M., Bailey, D. A., Refsnider, K. A., Lehman, S. J., Southon, J. R., Anderson, C., Björnsson, H., and Thordarson, T.: Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks, Geophys. Res. Lett., 39, L02708, doi:10.1029/2011GL050168, 2012.

National Research Council: Surface Temperature Reconstructions for the Last 2000 Years, The National Academies Press, Washington, DC, 141 pp., 2006.

PAGES: Science Plan and Implementation Strategy (IGBP Report No. 57), Stockholm: IGBP Secretariat, 67 pp., 2009.

PAGES 2K Consortium: Continental-scale temperature variability during the last two millennia, Nat. Geosci., 6, 339–346, 2013.

Shao, X. M. and Wu, X. D.: Tree-ring chronologies for Pinus armandi Franch from Huashan, China, Acta Geographica Sinica, 49, 174–181, 1994.

Shen, J., Zhang, E. L., and Xia, W. L.: Records from lake sediments of the Qinghai Lake to mirror climatic and environmental changes of the past about 1000 year, Quat. Sci., 21, 508–513, 2001 (in Chinese).

Shen, X. Y. and Chen, J. Q.: Grain production and climatic variation in Taihu Lake Basin, Scientia Geographica Sinica, 11, 207–212, 1991 (in Chinese).

Shi, F., Yang, B., and Von Gunten, L.: Preliminary multiproxy surface air temperature field reconstruction for China over the past millennium, Science China: Earth Sciences, 55, 2058–2067, 2012.

Tan, M., Hou, J. Z., Qin, X. G., Zhang, H. C., and Li, T. Y.: Cyclic rapid warming on centennial scale revealed by a 2650-year stalagmite record of warm season temperature, Geophys. Res. Lett., 30, 1617–1621, 2003.

Tang, G. L., Ding, Y. H., Wang, S. W., Ren, G. Y., Liu, H. B., and Zhang, L.: Comparative analysis of the time series of surface air temperature over China for the last 100 years, Advances in Climate Change Research, 5, 71–78, 2009.

Thompson, L. G., Yao, T., Mosley-Thompson, E., Davis, M. E., Henderson, K. A., and Lin, P. N.: A high-resolution millennial record of the South Asian Monsoon from Himalayan ice cores, Science, 289, 1916–1919, 2000.

Thompson, L. G., Mosley-Thompson, E., Davis, M. E., Lin, P. N., Henderson, K., and Mashiotta, T. A.: Tropical glacier and ice core evidence of climate change on annual to millennial time scales, Climatic Change, 59, 137–155, 2003.

Thompson, L. G., Yao, T., Davis, M. E., Mosley-Thompson, E., Mashiotta, T. A., Lin, P. N., Mikhalenko, V. N., and Zagorodnov, V. S.: Holocene climate variability archived in the Puruogangri ice cap on the central Tibetan Plateau, Ann. Glaciol., 43, 61–69, 2006.

Wang, N. L., Yao, T. D., Pu, J. C., Zhang, Y. L., and Sun, W. Z.: Climatic and environmental changes over the last millennium recorded in the Malan ice core from the northern Tibetan Plateau, Sci. China Ser. D, 49, 1079–1089, 2006.

Wang, R. S. and Wang, S. W.: Reconstruction of winter temperature in east China during the last 500 years using historical documents, Acta Meteorologica Sinica, 48, 180–189, 1990 (in Chinese).

Wang, S. W., Ye, J. L., and Gong, D. Y.: Climate in China during the Little Ice Age, Quat. Sci., 25, 54–621, 1998 (in Chinese).

Wang, S. W., Wen, X. Y., Luo, Y., Dong, W. J., Zhao, Z. C., and Yang, B.: Reconstruction of temperature series of China for the last 1000 years, Chinese Sci. Bull., 52, 3272–3280, 2007.

Yang, B., Braeuning, A., Johnson, K. R., and Shi, Y. F.: General characteristics of temperature variation in China during the last two millennia, Geophys. Res. Lett., 29, 1324, doi:10.1029/2001GL014485, 2002.

Yao, T., Thompson, L. G., Mosley-Thompson, E., Yang, Z., Zhang, X., and Lin, P.: Climatological significance of δ^{18}O in north Tibetan ice cores, J. Geophys. Res., 101, 29531–29537, 1996.

Zhang, D. E.: Winter temperature changes during the last 500 Years in South China, Chinese Sci. Bull., 6, 497–500, 1980,

Zhang, P. Y.: Climate change in China during historical times, Scientific and Technological Press, Jinan, China, 435–436, 1996.

Zhang, Y., Shao, X. M., and Yin, Z. Y.: Millennial temperature variations derived from tree-ring width chronologies at the upper treeline of the Qilian Mountains, the Tibetan Plateau, XVIII INQUA Congress, Bern, Switzerland, 21–27 July 2011, Abstract No. 1705, 2011.

Zheng, J. Y. and Zheng, S. Z.: An analysis on cold/warm and dry/wet in Shandong Province during historical times, Acta Geographica Sinica, 48, 348–357, 1993 (in Chinese).

Zheng, S. Z.: Climate in the Little Ice Age and its effects in Guangdong, China, Chinese Sci. Bull., 27, 302–304, 1982 (in Chinese).

Zhu, H. F., Zheng, Y. H., Shao, X. M., Liu, X. H., Xu, Y., and Liang, E. Y.: Millennial temperature reconstruction based on tree-ring widths of Qilian juniper from Wulan, Qinghai Province, China, Chinese Sci. Bull., 53, 3914–3920, 2008.