JOURNAL OF QUATERNARY SCIENCE (2009) **24**(5) 547–551
Copyright © 2009 John Wiley & Sons, Ltd.
Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/jqs.1298

Comparative analysis between a proxy-based climate reconstruction and GCM-based simulation of temperatures over the last millennium in China

MING TAN,[1]* XUEMEI SHAO,[2] JIAN LIU[3] and BINGGUI CAI[1]
[1] Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China
[2] Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China
[3] State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing, China

Tan, M., Shao, X., Liu, J. and Cai, B. 2009. Comparative analysis between a proxy-based climate reconstruction and GCM-based simulation of temperatures over the last millennium in China. *J. Quaternary Sci.*, **Vol. 24** pp. 547–551. ISSN 0267-8179.

Received 22 March 2008; Revised 20 April 2009; Accepted 22 April 2009

ABSTRACT: The application of general circulation models (GCMs) could improve our understanding of climate forcing. Furthermore, longer climate records spanning a wider range of climate states could help in assessing the skill of the models for simulating climates different from the present. We first attempt to find a way to combine proxy records which are affected by different seasonal temperatures, and then present a large-scale temperature reconstruction over the last millennium for China by combining the Beijing stalagmite layer series and the Qilian tree ring sequence to compare with the GCM-based ECHO-G simulated millennial temperature record for China. The correlation coefficient between the simulated and the reconstructed temperature records is 0.61 based on a 31-year running mean (exceeding $P < 0.01$). An asymmetrical *V*-like low-frequency variation shown both by the combined proxy record and the simulated series is the major long-term pattern in the last millennial temperature in China, suggesting that solar irradiance as well as greenhouse gases could explain much of the low-frequency variations in the climate. However, there still exist high-frequency discrepancies between the two time series, which may be due to (1) the overestimated climatic effect of volcanoes within the GCM and/or (2) proxies which are not sensitive enough to respond to the volcanic eruptions. Copyright © 2009 John Wiley & Sons, Ltd.
Supporting information may be found in the online version of this article.

KEYWORDS: comparative analysis; millennial temperature; proxy reconstruction; ECHO-G simulation; stalagmite; tree ring; China.

Introduction

More and more hemispheric-scale temperature reconstructions over the past one to two millennia have been made to promote our understanding of anthropogenic global warming (e.g. Jones *et al.*, 1998; Mann *et al.*, 1999; Briffa, 2000; Crowley and Lowery, 2000; Esper *et al.*, 2002; Mann and Jones, 2003; Moberg *et al.*, 2005). To quantitatively recover the history of temperature changes in China, Chinese scientists reconstructed large-scale temperature for the past 1000–2000 a using multiple proxies of 10 a resolution (e.g. Yang *et al.*, 2002; Wang *et al.*, 2007) as well as historical documents of 10–30 a resolution (e.g. Ge *et al.*, 2003). In recent studies, the reconstructed temperature for China has played an important role in hemispheric-scale multi-proxy temperature reconstructions (e.g. Mann and Jones, 2003; Moberg *et al.*, 2005).

In addition to climate reconstruction, GCM-based model simulations might also provide further knowledge on climate variability (such as in Moberg *et al.*, 2005). So far, however, few authors have evaluated the differences between the reconstructions and the simulations. Here we attempt to combine the 2650 a stalagmite warm season temperature record from Beijing (Tan *et al.*, 2003) and the 1000 a tree ring cold season temperature record from Qilian Mountain (Liu *et al.*, 2007) (both have not yet been combined in the previous Chinese proxy temperature reconstructions mentioned above) for the following purposes: (1) to test the methodology for combining annual resolution climatic proxies of different materials responding to changes in temperature in different seasons; (2) to review the nature of the temperature over the last millennium in China; and (3) to analyse comparatively the proxy reconstruction and the simulation to provide an analysis

---

* Correspondence to: M. Tan, Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China.
E-mail: tanming@mial.iggcas.ac.cn

using longer and more accurate data than previously carried out (Liu *et al.*, 2005a).

Data and settings

The Qilian Mountains (37–39° N, 99–103° E) are located at the northeastern edge of the Tibetan Plateau, at the convergence of the Qinghai-Xizang (Tibet) Plateau, the Inner Mongolia–Xinjiang Plateau and the Loess Plateau, China. High temperature extremes range from 28.5 to 32.4°C and the low temperature extremes from −27.8 to −29.0°C at Sidalong Meteorological Station (2600 m elevation) near the sampling site. Annual precipitation ranges from 401.9 to 632.3 mm, the annual evaporation varies between 1041.2 and 1234.2 mm, and relative humidity is about 57%. Following the International Tree-Ring Data Bank (ITRDB) standards (Grissino-Mayer and Fritts, 1997), Qilian juniper samples were collected at Sidalong Forest Centre of Sunan County (38° 26′ N, 99° 56′ E) in October 2000. The sampled trees are generally growing on steep (42°) south-facing slopes near the timberline, where there is little disturbance due to human activities. Fifty cores were taken from 25 trees at elevations from 3400 to 3550 m in a relatively open stand. An increment borer was used to enable cross-dating and to establish tree ring width chronology.

Using basic procedures of tree ring analysis (Fritts, 1976) and of tree ring research in arid zones (Shao *et al.*, 2003), skeleton plotting was used for primary dating. Cross-dating was further checked using the computer program COFECHA (Holmes, 1983). In order to retain low-frequency information, we used conservative detrending methods to remove age-related growth trends (Fritts, 1976). Each tree ring series was fitted with a negative exponential curve, while preserving variations of all frequencies that may be related to climate (Cook and Kairiukstis, 1990). Using the ARSTAN function (Cook and Holmes, 1986), we synthesised a standard tree ring width chronology (RWC) using double-weighted average methods for detrending series (see Liu *et al.*, 2007, for details). The relationship of ring width to temperature from December of the previous year to April were significant, with correlation coefficients of 0.60 ($P < 0.001$). The results indicate that cold season temperature is a major factor limiting tree growth.

Beijing, about 1400 km away from the Qilian tree ring site and within the East Asian monsoon zone, typically has cold/dry winters and warm/wet summers. The current mean annual temperature is 12.3°C, while mean annual precipitation is 572 mm for the reference period 1971–2000. Shihua Cave (115° 56′ E, 39° 47′ N, 251 m above sea level at the entrance) is about 50 km southwest of downtown Beijing, where the stalagmite growth layers are well developed (Tan *et al.*, 1997). The cave was opened to the public in 1986, and since then CO_2 in the cave air has risen from 500–600 to 1350–2080 p.p.m.v., and the cave temperature has increased from 10.6–13.5 to 13.9–16.4°C. These changes in cave conditions have resulted in a reduced rate of calcite precipitation due to decreased degassing of carbon dioxide from drip water. Thus stalagmite growth layers formed after 1985 cannot be used to reconstruct climate. The 2650 a (665 BC to AD 1985) stalagmite layer thickness chronology (LTC) from Beijing Shihua Cave has been calibrated with the observed local warm season (May to August) temperature. The correlation coefficient between the layer thickness and the average warm season temperature is 0.68 (using 1951–1985 data). The mechanism of responding to the warm season temperature for the LTC is interpreted elsewhere (Tan *et al.*, 2003).

Reconstruction

The RWC spans the periods between AD 1000 and AD 2000, and the LTC spans the periods between 665 BC and AD 1985. The combined time series therefore should be the intersection between the two time series, i.e. the period between AD 1000 and AD 1985 (the LTC data are available on the WDC website: ftp://ftp.ncdc.noaa.gov/pub/data/paleo/speleothem/china/shihua_tan2003.txt).

The RWC represents yearly growth rate of the trees and the LTC represents yearly deposit rate of the stalagmite; therefore both the RWC and the LTC were standardised before combination. The standardised index (SI) for the two time series can be extracted from a simple equation: $\mathrm{SI} = (Y - Y') / S$, where Y is the yearly data, Y' is the average and S is the standard deviation. The data for standardisation in the equation are tree ring width and stalagmite layer thickness (Fig. 1).

By combining the yearly standardised variance of the two time series, i.e. calculating the arithmetic mean of both the SIs year by year, we obtain a new combined series BQ (i.e. BQ is

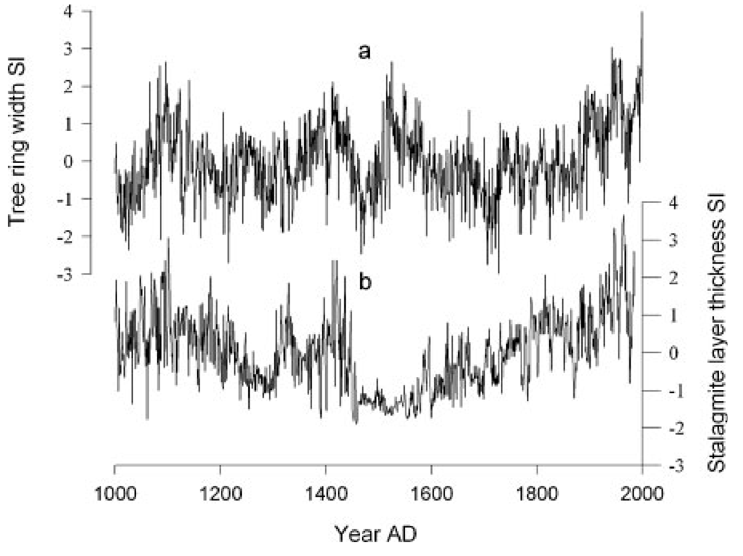

Figure 1 Normalisation of the tree ring width series from Qilian Mountain (a) and stalagmite growth layer thickness sequence from Beijing Shihua Cave (b) with the equation: standardised index $(\mathrm{SI}) = (Y - Y') / S$, where Y is the yearly data, Y' is the average and S is the standard deviation

the average of $SI_{stalagmite}$ and SI_{tree}). We first compare the 11 a running mean BQ with the temperature reconstruction on a 10 a resolution derived from multi-proxy records for the whole of China (Yang *et al.*, 2002) ($r = 0.56$). Secondly, we compare the BQ with the temperature reconstruction derived from tree rings for the Northern Hemisphere (Esper *et al.*, 2002) ($r = 0.53$ for 11 a running means). These results point convincingly to an explanation that the BQ could provide large-scale and low-frequency temperature signals.

Wang *et al.* (1998) presented a 119 a temperature database for the whole of China, which consists of the observed data (AD 1951–1998) and the mix of proxy and observed data (AD 1880–1950). These data are the departures from the mean of temperatures from 1961 to 1990. Here, we add the average annual mean temperature from 1961 to 1990 to each temperature departure value to back-calculate the actual annual temperature, and then calibrate the BQ with the annual data of Wang *et al.* (1998). The calibration equation is $Y = 0.176\ X + 11.121$, where Y is temperature, X is the BQ, correlation coefficient $r = 0.34$, $n = 106$, $P < 0.001$, residual sum of squares = 14.35 and regression sum of squares = 1.75.

The uncertainty of the reconstruction should be considered, which is largely caused by calibration, in which the linear regression procedure produces a residual sum of squares, and then the standard deviation of the residuals is used as an estimation of the standard error (ESE). The $ESE = \sqrt{[s\ /\ (n - p)]} = \pm 0.37^{\circ}C$, where s is the sum of the squared residuals, n is the number of data points and p is the number of parameters in the regression model.

In addition, measurement of the tree ring and the stalagmite lamina can produce very small errors which have been involved in calibration uncertainty (such measurement error was reported by Tan *et al.* (2003); see the data on the website: ftp://ftp.ncdc.noaa.gov/pub/data/paleo/speleothem/china/shihua_tan2003.txt).

Based on the calibration, the combined annual mean temperature with high levels of uncertainty caused by the calibration as well as the measurements over the last millennium is derived for China (Fig. 2). The result shows that there were two maxima for temperature before AD 1450: one appeared at about AD 1100 and the other at AD 1413. The reconstructed temperature in China is therefore characterised by a double-peak pattern during Medieval times. Troughs in the temperature record coincided with the minima of solar activity; specifically, they are consistent with the Wolf Minimum and the Spörer Minimum, as well as the Maunder Minimum (see the horizontal blocks in Fig. 2). Based on cosmogenic nuclide records, Bard *et al.* (2000) reconstructed millennial solar activity, and later the solar irradiance series was temporally interpolated by Mann *et al.* (2005). Here we compare the temperature reconstruction with the Mann *et al.* (2005) series; the correlation coefficient between them is 0.55 ($P < 0.001$) for an 11a running mean. This relationship strongly supports the argument for the role of solar activity in the reconstruction.

Simulation

We have previously undertaken a multi-proxy study of a similar topic in 2005 using data covering the period AD 1550–1990 (Liu *et al.*, 2005a) and also simulated the winter temperature in eastern China (Liu *et al.*, 2005b) for comparison with the relevant reconstructed time series (Ge *et al.*, 2003). To understand better the changes and mechanisms of Chinese temperature over the last millennium, we develop this analysis further here using longer and more accurate data.

A millennial simulation from the GCM ECHO-G (von Storch *et al.*, 2004) is compared to our reconstructions. The model consists of the spectral atmospheric model ECHAM4 and the global ocean circulation model HOPE-G; both were implemented and developed at the Max Planck Institute of Meteorology (MPI) in Hamburg. The model ECHO-G was driven by three external forcing factors: solar variability, greenhouse gas concentrations in the atmosphere (including CO_2 and CH_4) and an estimation of radiative effects of stratospheric volcanic aerosols (Crowley, 2000) for the period AD 1000–1990 (González-Rouco *et al.*, 2003; Zorita *et al.*, 2005). Further details of the simulations can be found in von Storch *et al.*, 2004.

The solar variability, greenhouse gas concentrations in the atmosphere and an estimation of radiative effects of stratospheric volcanic aerosols data have been supplied as supporting information.

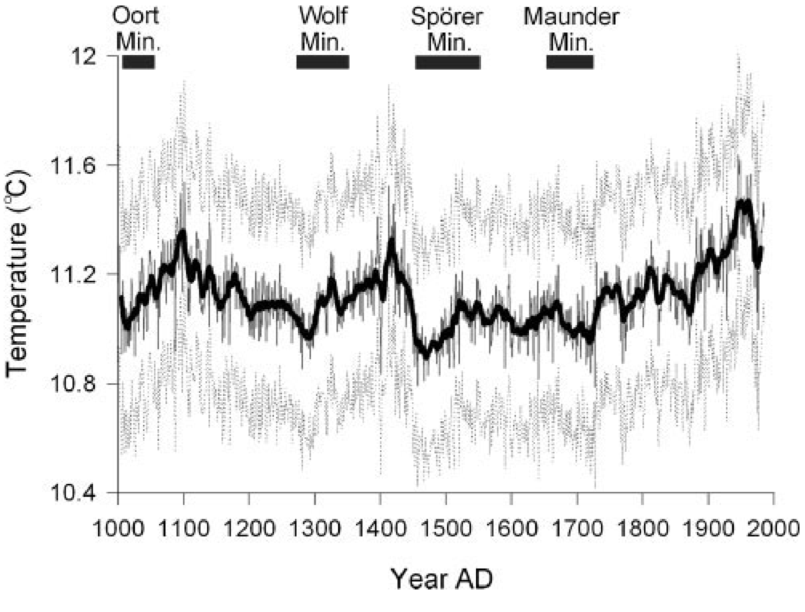

Figure 2 Combined 1000 a temperature reconstruction derived by calibrating the BQ (BQ is the average of $SI_{stalagmite}$ and SI_{tree}) with the temperature records of China (Wang *et al.*, 1998, using the data of 1880–1985). The thick line is 11 a running mean, and the dashed lines show the uncertainty expressed by standard error (see text for details). The horizontal blocks indicate the solar minimum periods

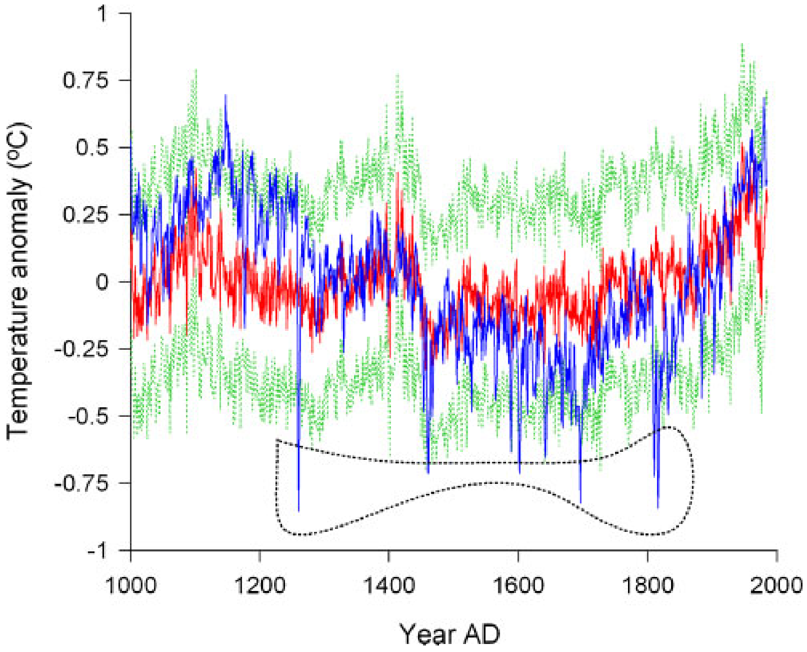

Figure 3 Comparison of the combined 1000 a temperature record (red) with the simulated result produced with the ECHO-G model (blue). Both anomalies are relative to the same reference period (AD1000–1985, i.e. departure from the average over the whole time series). The green dashed lines show the uncertainty of reconstruction expressed by standard error. Periods of discrepancy between the two time series are circled by the black dotted line

Comparative analysis

Despite the uncertainty of the reconstruction being high, we find that the anomalies of the reconstruction and simulation relative to the same reference period AD 1000–1985 (i.e. departures from the average over the whole time series) possess the same low-frequency components, which exhibit an asymmetrical *V*-like shape (red and blue lines in Fig. 3). The correlation coefficients between the two time series are $r=0.58$, $r=0.63$ for 11 a running mean and 31 a running mean, respectively, which suggests that there is a strong coincidence between the two series. These correlations indicate a stronger relationship than that between the simulation and the winter half-year reconstruction (Liu *et al.*, 2005b: $r=0.37$ for 10 and 30 a resolution). The results indicate that solar variability as well as the greenhouse gas forcing could explain much of the low-frequency variation in temperature over the last millennium at these sites.

However, some discrepancies between the reconstructed and the simulated series are distinctive, mainly in the high-frequency changes (the part circled by the black dotted line in Fig. 3). The climate pattern derived from the simulation is notable for the very sharp drops in temperature, down to 0.3–1.25°C within very short time spans, which has never been found in any regional or hemispherical temperature reconstructions, inferring that the climatic effect of volcanic eruptions may be overestimated by the model and/or the proxy may not be sensitive enough to respond to the volcanic forcing.

Conclusion

We provide the first example of combining annual-resolution proxy data to reconstruct large-scale temperature over the last millennium for China. Wide comparisons of the reconstruction with the Northern Hemisphere temperature records, reconstructed solar activity and a model simulated temperature series show that the methodology used in this study is suitable and convincing. Simple procedures can be employed to combine climate proxies as long as they contain a similar climate signal on the same temporal resolution.

An asymmetrical *V*-like low-frequency variation, which is shown both by the combined proxy record and the simulated series in this paper, as well as exhibited by most of the Northern Hemisphere temperature reconstructions, is the major long-term pattern in the last millennial temperature in China, which implies that solar irradiance as well as greenhouse gases could explain much of the low-frequency variations in the climate.

Some discrepancies between the reconstruction and the simulation, mainly in the high-frequency component, may be due to an overestimated climatic effect of volcanic eruptions by the simulation and/or insensitivity in the proxies. Comparative analysis between climate reconstruction and simulation could not only improve our understanding of the climate change but also reveal unexpected problems in the reconstruction and the simulation.

Acknowledgements We thank Prof. Andy Baker for his helpful suggestions on the early draft and the final version of the paper. Thanks also to Dr Mary Gagen and Dr Iain Robertson for making grammatical corrections to the text. We thank Dr Eduardo Zorita, Dr Jesus Fidel Gonzalez Rouco, Prof. Hans von Storch and Prof. Bin Wang for their help on ECHO-G simulation and comments on the manuscript. We appreciate the constructive comments from three anonymous reviewers. This work was supported by the National Natural Science Foundation of China (grant no. 90502009), the Chinese Academy of Sciences (grant nos KZCX2-YW-316 and KZCX2-YW-315) and the National Basic Research Program of China (grant nos 2006CB400503 and 2004CB720208).

References

Bard E, Raisbeck G, Yiou F, Jouzel J. 2000. Solar irradiance during the last 1200 yr based on cosmogenic nuclides. *Tellus Series B* **52**: 985–992.

Briffa KR. 2000. Annual climate variability in the Holocene: interpreting the message of ancient trees. *Quaternary Science Review* **19**: 87–105.

Cook ER, Holmes RL. 1986. *User manual for ARSTAN Laboratory of Tree Ring Research*. University of Arizona, Tucson, AZ.

Cook ER, Kairiukstis LA (eds). 1990. *Methods of Dendrochronology*. Kluwer: Dordrecht.

Crowley TJ. 2000. Causes of climate change over the past 1000 years. *Science* **289**: 270–277.

Crowley TJ, Lowery TS. 2000. How warm was the Medieval Warm Period? *AMBIO* **29**: 51–54.

Esper J, Edward RC, Schweingruber FH. 2002. Low frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science* **295**: 2250–2253.

Fritts HC. 1976. *Tree Rings and Climate*. Academic Press: London.

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

González-Rouco JF, von Storch H, Zorita E. 2003. Deep soil temperature as proxy for surface air-temperature in a coupled model simulation of the last thousand years. *Geophysical Research Letters* **30**: 2116.

Holmes RL. 1983. Computer assisted quality control in tree ring dating and measurement. *Tree-Ring Bulletin* **43**: 69–6975.

Jones PD, Briffa KR, Barnett TP, Tett FSB. 1998. High-resolution paleoclimatic records for the last millennium: Interpretation, integration and comparison with General Circulation Model control run temperatures. *The Holocene* **8**: 467–473.

Liu J, von Storch H, Zorita E, Chen X, Wang S. 2005a. Simulated and reconstructed temperature in China since 1550 AD. *History of Meteorology* **2**: 87–104.

Liu J, von Storch H, Chen X, Zorita E, Zheng J, Wang S. 2005b. Simulated and reconstructed winter temperature in eastern China during the last millennium. *Chinese Science Bulletin* **50**: 2872–2877.

Liu X, Shao X, Zhao L, Qin D, Chen T, Ren J. 2007. Dendroclimatic temperature record derived from tree-ring width and stable carbon isotope chronologies in the Middle Qilian Mountains, China. *Arctic, Antarctic, and Alpine Research* **39**: 651–657.

Mann ME, Jones PD. 2003. Global surface temperatures over the past two millennia. *Geophysical Research Letters* **30**: 1820.

Mann ME, Bradley RS, Hughes MK. 1999. Northern hemisphere temperature during the past millennium: inferences, uncertainties, and limitations. *Geophysical Research Letters* **26**: 759–7762.

Mann ME, Cane MA, Zebiak SE, Clement A. 2005. Volcanic and solar forcing of the tropical Pacific over the past 1000 years. *Journal of Climate* **18**: 417–456.

Moberg A, Sonechkin DM, Holmgren K, Datsenko NM, Karlén W. 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature* **433**: 613–617.

Shao XM, Fang XQ, Liu HB, Huang L. 2003. Dating the 1000-year-old Qilian juniper in mountains along the eastern margin of the Qaidam Basin. *Acta Geographica Sinica* **58**: 90–100.

Tan M, Liu T, Qin X, Zhang D. 1997. Microbanding of stalagmite and its significance. *PAGES News* **5**: 6–7.

Tan M, Liu T, Hou J, Qin X, Zhang H, Li T. 2003. Cyclic rapid warming on centennial-scale revealed by a 2650-year stalagmite record of warm season temperature. *Geophysical Research Letters* **30**: 1617–1620.

von Storch H, Zorita E, Jones JM, Yegor D, González-Rouco F, Tett SFB. 2004. Reconstructing past climate from Noisy data. *Science* **306**: 679–682.

Wang S, Ye J, Gong D, Zhu J, Yao T. 1998. Construction of mean annual temperature series for the last one hundred years in China (in Chinese). *Journal of Applied Meteorological Science* **9**: 392–401.

Wang SW, Wen XY, Luo Y, Dong WJ, Zhao ZC, Yang B. 2007. Reconstruction of temperature series of China for the last 1000 years. *Chinese Science Bulletin* **52**: 3272–3280.

Yang B, Braeuning A, Johnson KR, Shi Y. 2002. General characteristics of temperature variation in China during the last two millennia. *Geophysical Research Letters* **29**: 381–384.

Zorita E, González-Rouco JF, von Storch H, Montávez JP, Valero F. 2005. Natural and anthropogenic modes of surface temperature variations in the last thousand years. *Geophysical Research Letters* **32**: L08707.