Cyclic rapid warming on centennial-scale revealed by a 2650-year stalagmite record of warm season temperature

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Received 18 March 2003; revised 18 March 2003; accepted 29 April 2003; published 19 June 2003.

[1] A 2650-year (BC665-AD1985) warm season (MJJA: May, June, July, August) temperature reconstruction is derived from a correlation between thickness variations in annual layers of a stalagmite from Shihua Cave, Beijing, China and instrumental meteorological records. Observations of soil CO_2 and drip water suggest that the temperature signal is amplified by the soil-organism-CO_2 system and recorded by the annual layer series. Our reconstruction reveals that centennial-scale rapid warming occurred repeatedly following multicentenial cooling trends during the last millennia. These results correlate with different records from the Northern Hemisphere, indicating that the periodic alternation between cool and warm periods on a sub-millennial scale had a sub-hemispherical influence. *INDEX TERMS:* 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 9320 Information Related to Geographic Region: Asia; 4863 Oceanography: Biological and Chemical: Sedimentation. **Citation:** Tan, M., T. S. Liu, J. Hou, X. Qin, H. Zhang, and T. Li, Cyclic rapid warming on centennial-scale revealed by a 2650-year stalagmite record of warm season temperature, *Geophys. Res. Lett.*, *30*(12), 1617, doi:10.1029/2003GL017352, 2003.

1. Introduction

[2] Laminated stalagmites have been used as high-resolution climatic indicators since the growth layers were verified to be annual by ^{14}C [*Broecker et al.*, 1960] and TIMS-^{230}Th [*Baker et al.*, 1993] methods. An annual layer series of alternating aragonite and calcite from Botswana shows that the thickness of calcite layers correlates with rainfall and the thickness of aragonite layers correlates with temperature [*Raisback et al.*, 1994]. Annually laminated sequences in some Belgian stalagmites demonstrate that layer growth is primarily controlled by rainfall [*Genty and Quinif*, 1996]. Layered stalagmites from Anjohibe Cave have provided a high-resolution proxy record of rainfall and ENSO events since AD 1550 [*Brook et al.*, 1999]. A speleothem from Scotland gives a thousand-year proxy record of North Atlantic climate [*Proctor et al.*, 2000]. Color variations in annual growth layers have been used in a preliminary 3000-year regional temperature reconstruction for South Africa [*Holmgren et al.*, 2001]. Stalagmite growth layers thus seem sensitive not only to rainfall, but also to temperature in different environments. By comparing TIMS-^{230}Th dating with layer counting, we have characterized microscopic features to identify annual layers for many stalagmites from China [*Tan et al.*, 2000; *Hou et al.*, 2002]. Here we report a warm season temperature reconstruction (WTR) from a stalagmite from Shihua Cave, Beijing, which provides evidence of cyclical rapid warming on a centennial-scale over the last millennia.

2. Setting and Observations

[3] Beijing, within the East Asian monsoon zone, typically has cold/dry winters and warm/wet summers. The current mean annual temperature is 11.8°C while mean annual precipitation is 577 mm. Shihua Cave (115°56′E, 39°47′N, 251 m above sea level at the entrance) is about 50 km southwest of downtown Beijing. The cave was opened to the public in 1986. Since then, CO_2 in the cave air has risen from 500–600 to 1350–2080 ppmv, 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. So, stalagmite growth layers formed after 1985 cannot be used to reconstruct climate. We once assumed that variations in layer thickness might respond principally to rainfall due to their matched amplitudes [*Qin et al.*, 1999]. After understanding the mechanism responsible for amplifying the climate signal in the soil, we can reconstruct climate using stalagmite layer thickness.

[4] According to observations near Shihua Cave [*Tang and Zhou*, 1999], the relationship between soil CO_2 (C) and atmospheric temperature (T) can be expressed as $\ln(C) = 0.0657T + 6.4941$ ($r = 0.85$, $p < 0.001$). This means that a

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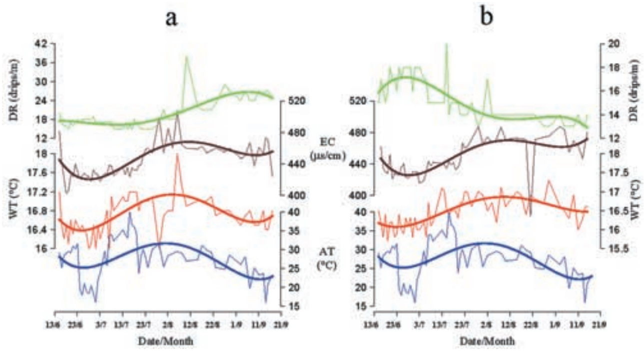

Figure 1. Observation of drip water at different depths (site a elevation is higher than site b) in Shihua Cave, including drip rate (DR, green), electrical conductivity (EC, brown) and water temperature (WT, red) compared with atmospheric temperature (AT, blue, maximum daily temperature) within the interval from June, 13th to September, 14th, 2002. Thick lines, data smoothed by a 4th-order polynomial filter, show monthly trends (daily fluctuations contain a lot of noise).

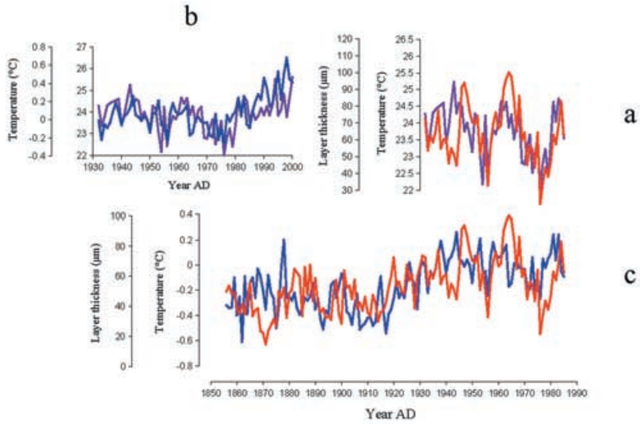

Figure 2. Comparison between the observed temperature and the LTC (see text). (a), Comparison of observed Beijing MJJA temperature (purple) and the LTC (red) from 1930 to 1985. Timescale is the same as that in (c). (b), Comparison of observed Beijing MJJA temperature (purple) and observed NH annual mean temperature (blue) from 1930 to 2000. (c), Comparison of the LTC (red) and observed NH mean annual temperature (blue) from 1856 to 1985 [Observed data for Beijing from website: http://www.giss.nasa.gov/cgi-bin/update/name (lack of 1938). NH data from website: http://www.cru.uea.ac.uk/cru/data/temperature/].

little change in atmospheric temperature can lead to a significant change in soil CO_2, which controls the quantity of dissolved and subsequently deposited carbonate. Further calculation indicates that the weighted content of HCO_3^- in groundwater in July was about 246 times higher than in June (1998) due to higher soil CO_2 content, 5000 ppmv versus 3500 ppmv, respectively.

[5] Drip water rate in Shihua Cave normally increases during summer in response to heavier summer rainfall. Observations of drip water temperature (WT), drip rate (DR) and electrical conductivity (EC) are taken in the cave and compared with atmospheric temperature (AT, maximum daily temperature) for the warm season of 2002. Figure 1 shows that within the observed warm season interval, that AT controls WT, and WT is closely associated with EC, which is related to the content of carbonate in drip water on a monthly-scale. In contrast, there is an uncertain correlation between EC and DR. Figure 1a shows a weak positive correlation between EC and high DR, whereas Figure 1b shows a strong negative correlation between EC and low DR. This suggests that annual layer thickness of a stalagmite with a high growth rate may record rainfall. However, both cases suggest that warm season temperature may play an important role in layer thickness variations. In addition, a negative correlation (−0.41) between MJJA rainfall and MJJA temperature in Beijing (1951–2000) supports the assertion that MJJA temperature can independently influence the interannual variation in growth layer thickness. It also suggests that rainfall is always sufficient for layer growth during the warm season in the monsoon zone, and thus is a minor control on layer growth.

3. Sample and Methods

[6] The chronology of stalagmite TS9501 from Shihua Cave has been studied in detail [*Tan et al.*, 2002]. Since it was actively growing when collected in November 1995, its topmost layer is known to have formed in that year. We have identified all missing top layers post-1980 with an ameliorated optical system. The topmost layer is incomplete at the edge of the cut section due to polishing, thus measurement of the layer thickness starts from 1994 back in time. Under a BX60 Olympus microscope, annual layers are counted and re-measurements are taken along different routes, near and parallel to the growth axis, except where individual layer thickness is constant, and only averaged data is used. A small uncertainty in counting chronology was introduced by the presence of cracks on the thin section, which makes a little difference in the number of layers between counts along different routes and results in an absolute age error of five years. The layer thickness chronology (LTC) thus spans 2650 ± 5 years (BC 665-AD1985), and is accompanied by absolute measured errors of ±1.25 um (using 20 × objective lens) and ±0.625 um (using 40 × objective lens).

[7] Any non-climatic influence must be removed before the LTC can be used for climate reconstruction, and analyses of non-climate factors are therefore needed. In addition to temperature and rainfall, layer growth rate may be driven to some extent by changes in seepage water paths and surface vegetation. Changes in seepage water paths may deform the shape of stalagmites and alter the climate signal. We thus use only columnar stalagmites (see Supplementary Figure a)[1], which most likely remained under a steady hydrological state. Even so, any sedimentary trend formed at an early stage of growth, as the product of deposit-geometry, should be removed (see Supplementary Figure b). A prominent change in vegetation could affect the amount of soil CO_2, giving a pseudo-signal. Unfortunately, it seems

[1] Supporting material is available via Web browser or via Anonymous FTP from ftp:/ftp.agu.org, directory "apend" (Username = "anonymous", Password = "guest"); subdirectories in the ftp site are arranged by paper number. Information on searching and submitting electronic suppplements is found at http://www.agu.org/pubs/esupp_about.html.

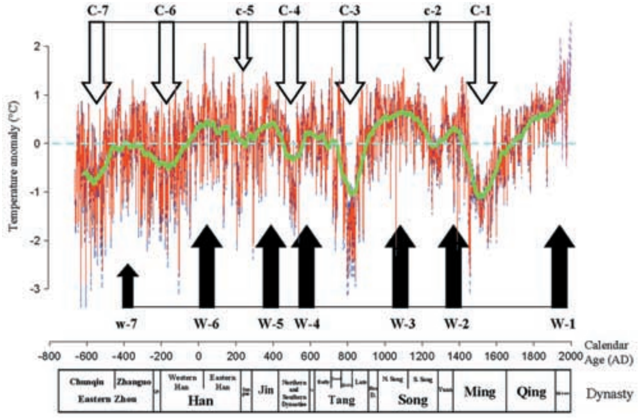

Figure 3. 2650-year (BC665-AD1985) WTR (see text) spliced with Beijing instrumental data from 1930-2000. Solid red line is reconstructed MJJA temperature. Dark blue dashed line is errors. Pink dashed line is observed MJJA data. The 101-year low-pass filter (green solid line) shows centennial-scale variation. The zero line (light blue dashed) corresponds to the overall mean of the reconstructed series. Thick and long arrows with capital letters W and C point out the "absolute" warm peaks (upward) and cool troughs (downward), respectively, at which temperature exceeds the average. Thin and short arrows with small letter *w* and *c* point out the "relative" warm peaks and cool troughs, respectively, at which temperature doesn't exceed the average.

impossible to evade the case by selecting samples. Signal-tests of the LTC therefore are absolutely necessary.

[8] Comparison of the LTC with the standardized instrumental records of Beijing (1951–1985) indicates that about 48% of the variation in layer thickness can be explained by MJJA temperature, and about another 10% by April precipitation according to separate regressions. Since observed temperature data for Beijing have multi-year gaps prior to 1930, the observed data between 1930 to 1985 (lack of 1938) provide calibration for the LTC (Figure 2a, r = 0.55, $p < 0.001$). Furthermore, to test the LTC with longer reliable Northern Hemisphere (NH) records, we first compare observed Beijing MJJA temperature data with both observed NH MJJA temperature (r = 0.44) and NH annual temperature (Figure 2b, r = 0.45, $p < 0.001$, 1930–2000), respectively. Since Beijing MJJA temperature correlates better with NH annual temperature, we then test the LTC with NH mean annual temperature for the period 1856 to 1985 (Figure 2c). The result indicates that the LTC correlates well with the NH mean temperature (r = 0.44 for yearly data and r = 0.87 for 20-year running means).

[9] However, care must be taken to extend any proxy climate indicator correlating well with instrumental records farther into the past. In this study, we use widely cited NH proxy temperature records to test the LTC for the interval prior to the period of instrumental records. First, reconstructed circum-Arctic temperature variability over the last 400 years [*Overpeck et al.*, 1997] was compared with the LTC. The result shows a pretty good correlation (r = 0.61, 5-year smoothed). Secondly, we compare the LTC with various 1000-year NH temperature records (10-year smoothed average) by *Jones et al.* [1998], *Mann et al.* [1999], *Crowley and Lowery* [2000] and *Esper et al.* [2002], which results in significant correlation coefficients of 0.48, 0.38, 0.54 and 0.45, respectively. The relationship between LTC and the record by Mann et al. is not as strong as the others, which may be due to one-third of the Mann et al. series being from the Southern Hemisphere (NH data are obtained from website: ftp://ftp.ngdc.noaa.gov/paleo/treering/reconstructions/n_hem_temp/briffa2001jgr3.txt).

4. Results and Discussions

[10] Based on these comparisons, we confirm that the LTC persistently reflects the temperature signal, which is not masked by noise. Thus, it is possible to reconstruct paleotemperature for Beijing with the LTC. By removing the sedimentary trend with a 3rd-order polynomial function [*Tan et al.*, 2002], a nonlinear regression of layer thickness against observed Beijing MJJA temperature for the period 1930–1985 yields the following exponential transfer function: $\ln(T) = 0.0567 \ln(L) + 2.9336$ (residual sum of squares = 0.0363, regression sum of squares = 0.0159, r = 0.55, $p < 0.001$), where T is MJJA temperature in °C and L the layer thickness in μm. The WTR then extends Beijing MJJA temperature back in time to BC665 (see Supplementary Dataset).

[11] In Figure 3, the 2650-year WTR is spliced into the instrumental MJJA records of 1930–2000 (overlap of 1930–1985). Because the LTC can better record a low-frequency temperature signal than a high-frequency one, the WTR is smoothed with a 101-year low-pass filter to emphasize multidecadal-to-centennial variations against the average of the overall sequence. It appears that warm and cool periods alternated cyclically on a centennial-scale throughout the past millennia. Power spectral analysis indicates that cycles of about 206 and 325 years are significant. We further test the WTR with the historical climate chronology (HCC) [*Shi and Zhang*, 1996], which has been studied in great detail by Chinese historical climate scientists since Chu K'o-chen first put forward his 5000-year

Table 1. Chinese Historical Climate Chronology [after *Shi and Zhang*, 1996]

Dynasty	Age (BC/AD)	Climate Period
Chunqiu	M 8th cent. – M 5th cent. BC	Warm Period
Zhanguo–E West Han	M 5th cent. – M 2th cent. BC	Cool Period
M West Han – L East Han	M 2th cent. BC– En 2th cent. AD	Warm Period
Wei & Jin – South–North D	E 3th cent. – M 6th cent. AD	Cool Period
Sui – Grand Tang	M 6th cent. –E 8th cent. AD	Warm Period
M Tang – E Five D	M 8th cent. – En 9th cent. AD	Cool Period
M Five D. – E Yuan	E 10th cent. – En 13th cent. AD	Warm Period (MWP)
L Yuan – L Qing	E 14th cent. – En 19th cent. AD	Cool Period (LIA)

E: Early; M: Middle; L: Late; D: Dynasty; En: End.

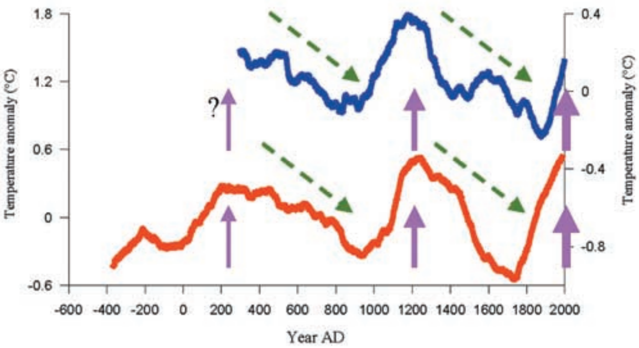

Figure 4. Shown are submillennial-scale saw-toothed alternations illustrated by the WTR (red) and the BTR (blue, see text), both are smoothed with a 300-year low-pass filter. Green arrows show a multicentennial cooling trend and red arrows indicate rapid warm peaks. The BTR data from the website http://www.cru.uea.ac.uk/cru/people/briffa/qsr1999/.

rough temperature profile [*Chu*, 1973]. The WTR agrees well with the HCC (Table 1), including the Medieval Warm Period (MWP) [*Lamb*, 1965] and the Little Ice Age (LIA) [*Matthes*, 1939]. An exception is the period centered on C-7, which is described as the "Chunqiu warm period" in the HCC. This discrepancy may be due to sparse documentary evidence in the ancient historical writings (the first author has discussed this with the some authors of the HCC).

[12] Power spectral analysis also indicates evident cycles of 758 and 900 years in the WTR. In fact, this sub-millennial-scale climatic pattern also occurred repeatedly in other longer, single proxy [*Briffa*, 2000] and heterogeneous [*Yang et al.*, 2002] large-scale temperature records, as well as individual [*Hong et al.*, 2000] and composite [*Bond et al.*, 2001] climate time series, which may infer at least a sub-hemispherical climate pattern. Smoothing the WTR and the temperature reconstruction by *Briffa* [2000] (BTR, a data-available high-resolution record from the NH) with a 300-year low-pass filter, reveals pronounced centennial-scale rapid warming: three in the WTR and two in the BTR. Each episode of warming followed a multicentennial-cooling trend (Figure 4), similar to the saw-toothed alternation of glacial/interglacial periods. All centennial to sub-millennial scale cycles exhibited by the WTR could be connected to solar variation cycles of about 208, 350, 700 and 950 years [*Lean*, 2002].

[13] **Acknowledgments.** We thank Xuemei Shao, Jingyun Zheng, Houyuan Lü, Guoqiang Chu, Zhisheng An and Hairuo Qing for their discussions and suggestions, and Guoxiang Sun for assistance of observations in the cave. We thank R. L. Edwards and Hai Cheng for their supporting previous TIMS-^{230}Th dating work, and thank all web data suppliers, which have been mentioned. This work was supported by the National Scientific Foundation of China (grants 49894170 and 40072098), the Chinese Ministry of Science and Technology (grant G1999043402) and the Chinese Academy of Sciences (grants KZCX2-SW-118 and KZCX3-SW-120). We specially thank two anonymous reviewers for their constructive suggestions that improved this contribution considerably.

References

Baker, A., P. L. Smart, R. L. Edwards, and D. A. Richards, Annual growth banding in a cave stalagmite, *Nature*, *364*, 518–520, 1993.

Bond, G., B. Kromer, J. Beer, R. Muscheler, M. N. Evans, W. Showers, S. Hoffman, R. Lotti-Bond, I. Hajdas, and G. Bonani, Persistent solar influence on North Atlantic climate during the Holocene, *Science*, *294*, 2130–2136, 2001.

Briffa, K. R., Annual climate variability in the Holocene: interpreting the message of ancient trees, *Quat. Sci. Rev.*, *19*, 87–105, 2000.

Broecker, W. S., E. A. Olson, and P. C. Orr, Radiocarbon measurement and annual rings in cave formations, *Nature*, *185*, 93–94, 1960.

Brook, A. G., et al., A high-resolution proxy record of rainfall and ENSO since AD 1550 from layering in stalagmites from Anjohibe Cave, Madagascar, *The Holocene*, *9*, 695–705, 1999.

Chu, K., A preliminary study on the climate fluctuations during the last 5000 years in China, *Science Sinica*, *16*, 226–237, 1973.

Crowley, T. J., and T. S. Lowery, How warm was the Medieval Warm Period?, *AMBIO*, *29*, 51–54, 2000.

Esper, J., R. C. Edward, and F. H. Schweingruber, Low Frequency Signals in Long Tree-Ring Chronologies for Reconstructing Past Temperature Variability, *Science*, *295*, 2250–2253, 2002.

Genty, D., and Y. Quinif, Annually laminated sequences in the internal structure of some Belgian stalagmites – importance for paleoclimatology, *Jour. Sedim. Res.*, *66*, 275–288, 1996.

Holmgren, K., P. D. Tyson, A. Moberg, and O. Svanered, A preliminary 3000-year regional temperature reconstruction for South Africa, *South African Journal of Science*, *97*, 49–51, 2001.

Hong, Y. T., et al., Response of climate to solar forcing recorded in a 6000-year $\delta^{18}O$ time-series of Chinese peat cellulose, *The Holocene*, *10*, 1–7, 2000.

Hou, J., M. Tan, and D. Liu, Counting chronology and climate records with about 1000 annual layers of a Holocene stalagmite from the Water Cave in Liaoning Province, China, *Science in China*, *45*, 385–391, 2002.

Jones, P. D., K. R. Briffa, T. P. Barnett, and F. S. B. Tett, High-resolution paleoclimatic records for the last millennium: Interpretation, integration and comparison with General Circulation Model control run temperatures, *The Holocene*, *8*, 467–473, 1998.

Lamb, H. H., The early Medieval warm epoch and its sequel, *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, *Climatic*, *1*, 13–37, 1965.

Lean, J., Solar forcing of climate change in recent millennia, in *Climate development and history of the North Atlantic realm*, edited by G. Wefer, W. H. Berger, K.-E. Behre, and E. Jansen, Berlin: Springer-Verlag, Heidelberg, 75–88, 2002.

Mann, M. E., R. S. Bradley, and M. K. Hughes, Northern hemisphere temperature during the past millennium: inferences, uncertainties, and limitations, *Geophysical Research Letters*, *26*, 759–762, 1999.

Matthes, F., Report of Committee on Glaciers, *Trans. Am. Geophys. Union*, *20*, 518–535, 1939.

Overpeck, J., et al., Arctic environmental change of the last four centuries, *Science*, *278*, 1251–1256, 1997.

Proctor, C. J., A. Baker, W. L. Barnes, and M. A. Gilmour, A thousand year speleothem proxy record of North Atlantic climate from Scotland, *Climate Dynamics*, *16*, 815–820, 2000.

Qin, X., et al., Spectral analysis of a 1000-year stalagmite lamina-thickness record from Shihua Cavern, Beijing, China, and its climatic significance, *The Holocene*, *9*, 689–694, 1999.

Raisback, L. B., G. A. Brook, J. Chen, R. Kalin, and C. J. Fleisher, Environmental control on the petrology of a late Holocene speleothem from Botswana with annual layer of aragonite and calcite, *Journal of Sedimentary Research*, *64*, 147–155, 1994.

Shi, Y., and P. Zhang (Eds.), *Climatic variation in historical time in China*, Shandong Scientific and Technique Press, Jinan, 1996 (in Chinese).

Tan, M., H. Cheng, R. L. Edwards, J. Hou, and T. Liu, TIMS-^{230}Th dating for very young annually laminated stalagmites, *Quaternary Sciences*, *20*, 391, 2000 (in Chinese).

Tan, M., J. Hou, and H. Cheng, Methodology of quantitatively reconstructing paleoclimate from laminated stalagmites, *Quaternary Sciences*, *22*, 209–219, 2002 (in Chinese).

Tang, C., and P. Zhou, The soil CO2 and its driving action on karstification in typical karst area in Beijing, *Carsologica Sinaca*, *18*, 213–217, 1999 (in Chinese).

Yang, B., A. Braeuning, K. R. Johnson, and Y. Shi, General characteristics of temperature variation in China during the last two millennia, *Geophys. Res. Lett.*, *29*, 381–384, 2002.

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