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Research paper

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Centennial- to decadal-scale monsoon precipitation variability in the semi-humid region, northern China during the last 1860 years: Records from stalagmites in Huangye Cave

Liangcheng Tan,[1] Yanjun Cai,[1] Zhisheng An,[1] R. Lawrence Edwards,[2] Hai Cheng,[2] Chuan-Chou Shen[3] and Haiwei Zhang[1]

Abstract

We developed a composite oxygen isotopic record of cave calcite for the last 1860 years based on three stalagmites from the Huangye Cave in eastern Gansu Province, northern China. The $\delta^{18}O$ values reflect monsoon precipitation changes, with lower $\delta^{18}O$ values representing higher precipitation and *vice versa*. Three intervals of high precipitation were identified at AD 138–450, AD 730–1200, and AD 1860–1960. Two intervals of low precipitation occurred at AD 1320–1410 and AD 1530–1860. The reconstructed monsoon precipitation variations correlate well with other records further east in the eastern Yellow River Basin, suggesting synchronous precipitation changes during the late Holocene in the semi-humid region of northern China on decadal to centennial scales. Peak periods of warfare in dynastic transition times, such as at AD 391–420, AD 601–630, AD 1111–1140, AD 1351–1380, and AD 1621–1650, correspond to sharp declines in precipitation or temperature in semi-humid northern China, indicating a strong connection between climatic and societal changes. Our study suggests that climatic deterioration in semi-humid northern China has played an important role in Chinese societal evolution.

Keywords

late Holocene, monsoon precipitation, northern China, societal change, stalagmite

Introduction

The semi-humid region of northern China covers an extensive area, ranging from eastern Gansu Province to the mid-lower reaches of the Yellow River and the Haihe River Basins (Liu, 1988) (Figure 1). This region is one of the most important cradles of Chinese civilization. Various cultures flourished here during the Neolithic Age, such as the Majiayao, Laoguantai and Yangshao, Peiligang and Dahecun, and Dawenkou culture systems (Zhang, 2006; and references therein). The region had been regarded as one of the core domination areas by the ruling dynasties of ancient China. Almost all the ruling dynasties established their capitals in this region since the Qin Dynasty (221–206 BC).

An *et al*. (2005) suggested that the evolution of Neolithic cultures in eastern Gansu was strongly influenced by climatic and environmental changes. The decline in rain-fed agricultural cultures and the reduced extent of human settlement after 4000 years BP (4 ka) in eastern Gansu may have been caused by a rapid transition from wet to dry climate at that time (An *et al*., 2005). Wu and Liu (2004) have also suggested that the dry event at 4 ka caused a decline in the Neolithic cultures of the mid-lower Yellow River Basin. Recently, Zhang *et al*. (2008) reported an 1810-year monsoon precipitation record based on the oxygen isotopic values of a stalagmite from Wanxiang Cave in eastern Gansu Province. By comparing the precipitation variations with the dynastic transitions in ancient China, they suggested that monsoon precipitation variations played an important role in the dynastic transitions during the periods AD 850–940, AD 1350–1380, and AD 1580–1640 (Zhang *et al*., 2008). However, increasing evidence in recent years has indicated that there are notable regional differences in the variability in monsoon precipitation in China on decadal to centennial scales (e.g. Cosford *et al*., 2008; Qian and Lin, 2005; Tan *et al*., 2009; Zhang *et al*., 2009). It has been suggested that the monsoon precipitation record reconstructed from the stalagmite in Wanxiang Cave might not properly represent the vast area influenced by the Asian summer monsoon (Zhang *et al*., 2009). More evidence is required to evaluate this important relationship between climate and culture (Kerr, 2008).

Here, we present an 1860-year record of monsoon precipitation in eastern Gansu Province, based on a composite oxygen isotopic record from three stalagmites collected from Huangye

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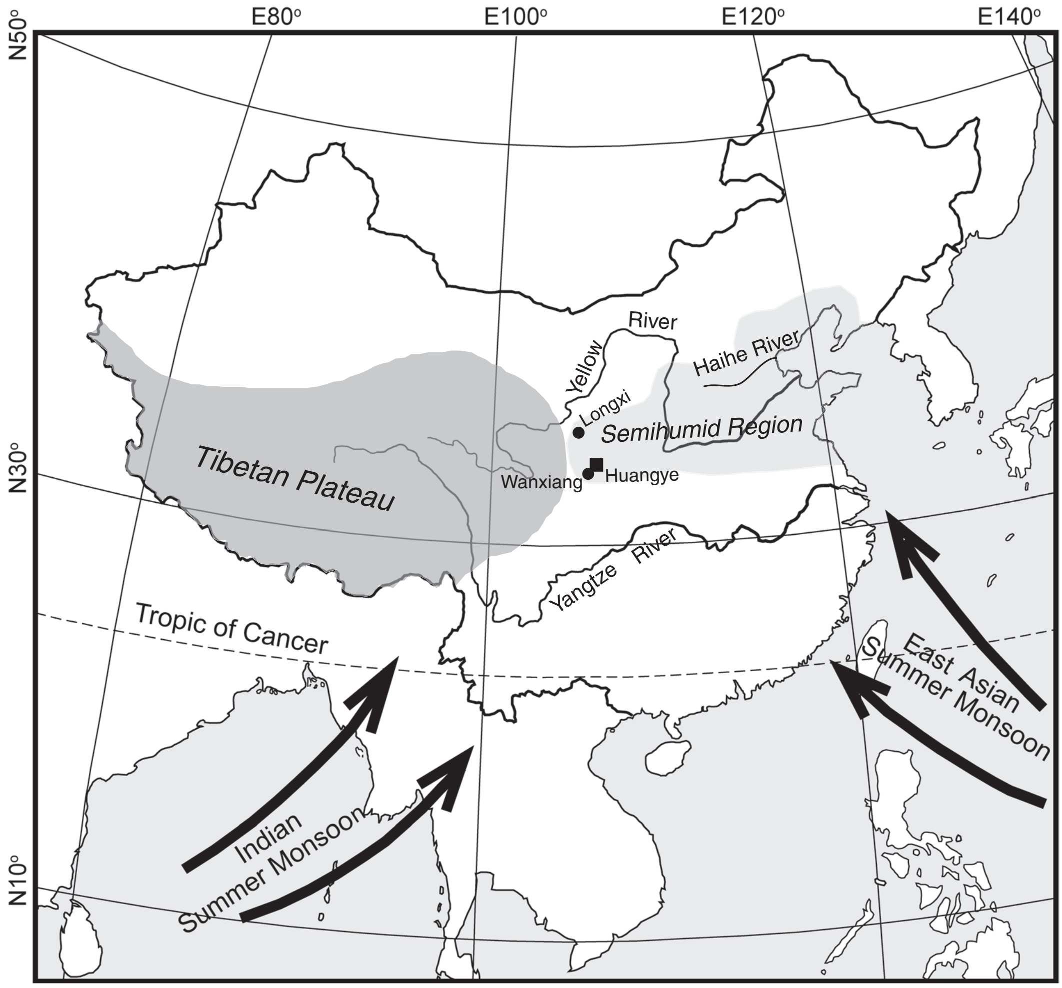

Figure 1. Locations of the Huangye Cave and the other sites mentioned in the text. The black-filled square indicates the Huangye Cave. The light grey area indicates the semi-humid region of northern China and the dark grey area indicates the Tibetan Plateau

Cave, ~30 km northeast of Wanxiang Cave. A comparison of the precipitation variations from this new record with those of other records in the mid-lower Yellow River Basin and the Haihe River Basin suggests the variability in precipitation was synchronous over the semi-humid region of northern China on decadal to centennial scales during the last 1860 years.

Cave location and climatology

The Huangye Cave (33°35′N, 105°07′E, 1650 m above sea level (a.s.l.) at its entrance) is located about 20 km northeast of Wudou County, eastern Gansu Province, China (Figure 1). The cave formed in Carboniferous limestone and is about 2 km long, 1–9 m wide, and 0.5–10 m high. No other shaft has been observed in the cave other than the single constricted entrance. The orientation and formation of the cave were controlled by the local fracture system that exhibits an E–W trend (Zhang *et al*., 2005). Huangye Cave is decorated with a variety of modern and fossil speleothems, including stalagmites, stalactites, and flowstones. The vegetation above the cave comprises secondary temperate forests and shrublands.

The climate in the region of the Huangye Cave is semi-humid and strongly affected by the Asian monsoon system. Most of the rainfall (~80%, for the period AD 1951–2003) occurs during the summer monsoon months (May–September). The mean annual temperature and precipitation (AD 1951–2003) recorded at the nearest meteorological station (Wudou station) are ~14.7°C and 480 mm, respectively.

Samples and methods

Three columnar stalagmites (Figure 2), with lengths of 9.4 cm for HY1, 20 cm for HY2, and 16 cm for HY3, were collected 0.6–1.0 km from the cave entrance in December 2006. Samples HY1 and HY3 were active stalagmites and the HY2 stalagmite had connected with the soda straw above it. The samples were cut along their growth axes and polished in the laboratory.

A total of 28 subsamples were drilled parallel to the growth planes of HY1, HY2, and HY3 (Figure 2) with a hand-held carbide dental drill, and were dated with U-series methods. The chemical procedure used to separate uranium and thorium followed those described by Edwards *et al*. (1987) and Shen *et al*. (2003). Measurements were made on a Finnigan Element sector-field inductively coupled plasma mass spectrometer (SF-ICP-MS) (Shen *et al*., 2002). The laminae in stalagmite HY3 were counted to construct its age model from the annual visible laminae observed on the polished surface of the stalagmite.

Powdered subsamples, used for stable isotope analyses, were drilled out using carbide dental burrs at intervals of 0.5 mm in HY1 and 1 mm in HY2 and HY3 along the central growth axes. The top 5 mm of HY2 had connected with the counterpart soda straw and was not subsampled. For this stalagmite,

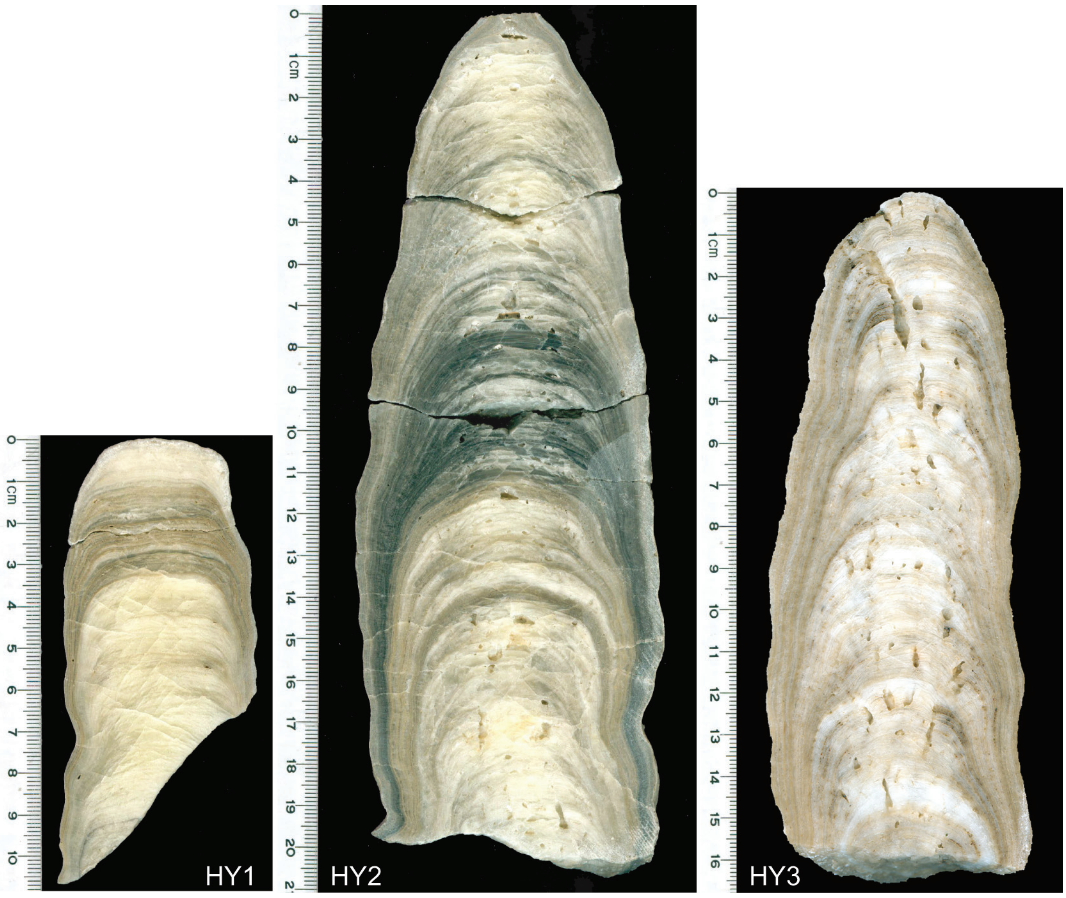

Figure 2. Polished sections of HY1, HY2, and HY3 collected from the Huangye Cave

the subsampling depth was relative to 6 mm, where the first subsample was drilled. Seven coeval subsamples from three horizons were selected from HY1 and HY2, respectively, for the 'Hendy test' (Hendy, 1971) to evaluate the isotopic equilibrium during calcite precipitation. Approximately 580 subsamples were measured on a Finnigan MAT-252 mass spectrometer equipped with a Kiel III Carbonate Device. The $\delta^{18}O$ values reported here are relative to the Vienna PeeDee Belemnite (VPDB) standard. Repeated measurements of one internal laboratory standard TTB1 showed that the long-term reproducibility of the $\delta^{18}O$ analyses was better than ±0.1‰ (2σ).

Results and discussion

Chronology

The SF-ICP-MS ^{230}Th dating results are shown in Table 1. For stalagmite HY1, all the subsamples measured are in stratigraphic order within errors, except for the date of HY1-7, which showed high detrital ^{232}Th levels of 1.4×10^4 part per trillion (ppt) and large dating uncertainties of ~200 years (Table 1). The exception was excluded from the established age model. The growth model of HY1 was developed using a linear interpolation method (Figure 3A). The model shows that HY1 grew from AD 760 to the present at rates ranging between 0.021 mm/yr and 0.178 mm/yr.

The growth model of HY2 was also developed using a linear interpolation method (Figure 3B). Compared with the time window of only 90 years between HY2-1 (AD 871 ± 24) and HY2-4 (AD 781 ± 45), the errors of ~80 years for the sandwiched subsamples HY2-2 and HY2-3, with high detrital ^{232}Th levels of 6–7 $\times 10^3$ ppt, are relatively large. Therefore, these two dates were not considered in the age model. The model shows that HY2 grew from AD 138 to 877 at rates ranging between 0.142 mm/yr and 0.503 mm/yr.

Because of the high detrital ^{232}Th levels of 1–3 $\times 10^4$ ppt, the best precision for the determined ^{230}Th ages are only ±72 years for HY3-2 and ±96 years for HY3-4. Because the HY3 stalagmite was actively growing when collected in the cave, its age model was constructed by counting the annual laminae (Figure 3C). The age model agrees with the two ^{230}Th dates for HY3-2 and HY3-4, suggesting a robust laminal chronology. The small discrepancy between the lamina-based chronology and the ^{230}Th dates for HY3-2 may have been primarily caused by the use of an initial $^{230}Th/^{232}Th$ atomic ratio of $4.4 \pm 2.2 \times 10^{-6}$. Although an initial $^{230}Th/^{232}Th$ atomic ratio of $4.4 \pm 2.2 \times 10^{-6}$ is widely used in U-series dating and has little effect on the dates of samples with high ^{238}U and low ^{232}Th concentrations (e.g. Cosford *et al*., 2008; Tan *et al*., 2009; Zhang *et al*., 2008), it may significantly affect the dates of samples with low ^{238}U and high ^{232}Th concentrations (e.g. Cai *et al*., 2005), like stalagmite HY3. The lamina-based chronology indicates that HY3 grew from AD 1308 to the present at relatively stable rates ranging between 0.200 mm/yr and 0.297 mm/yr.

Isotopic equilibrium tests

When studying oxygen isotopes in speleothems, it is desirable that the carbonate crystals are precipitated at or close to equilibrium conditions to limit the factors other than climate that affect the $\delta^{18}O$ signal. Hendy (1971) discussed the criteria for recognizing the conditions of equilibrium deposition, the so-called 'Hendy

Table 1. U-Th data and ^{230}Th dates for the three stalagmites from Huangye Cave

Sample ID	Depth (mm)	^{238}U (ppb)	^{232}Th (ppt)	δ^{234}U (measured)	^{230}Th / ^{238}U (activity)	^{230}Th age (yr) (uncorrected)	^{230}Th age (yr BP) (corrected)	^{230}Th age (yr AD) (corrected)	$\delta^{234}U_{Initial}$ (corrected)
HY1									
HY1-1	1.25	309 ± 1	2534 ± 13	696.9 ± 3.8	0.00314 ± 0.00015	202 ± 10	**4 ± 71**	**1946 ± 71**	697.0 ± 3.8
HY1-2	2.5	432 ± 1	2968 ± 7	696.8 ± 2.8	0.00346 ± 0.00022	223 ± 14	**48 ± 61**	**1902 ± 61**	697.0 ± 2.8
HY1-3	4.5	460 ± 1	1961 ± 5	702.2 ± 3.3	0.00324 ± 0.00021	207 ± 14	**78 ± 39**	**1872 ± 39**	702.5 ± 3.3
HY1-4	7.0	417 ± 1	826 ± 12	722.3 ± 3.5	0.00356 ± 0.00008	226 ± 5	**134 ± 18**	**1816 ± 18**	722.7 ± 3.5
HY1-5	11	522 ± 1	3927 ± 9	731.3 ± 3.6	0.00551 ± 0.00029	347 ± 18	**164 ± 66**	**1786 ± 66**	731.8 ± 3.7
HY1-6	17.5	595 ± 2	6330 ± 59	728.4 ± 8.2	0.01101 ± 0.00027	697 ± 18	**460 ± 91**	**1490 ± 91**	729.5 ± 8.3
HY1-7	26.75	632 ± 1	14142 ± 38	768.7 ± 3.6	0.01418 ± 0.00062	877 ± 39	**451 ± 188**	**1499 ± 188**	769.8 ± 3.6
HY1-8	34.5	629 ± 2	507 ± 2	691.9 ± 3.0	0.01110 ± 0.00015	717 ± 10	**646 ± 12**	**1304 ± 12**	693.3 ± 3.0
HY1-9	34.75	596 ± 1	472 ± 12	688.3 ± 3.5	0.01136 ± 0.00011	737 ± 7	**665 ± 10**	**1285 ± 10**	689.7 ± 3.5
HY1-10	48.75	612 ± 1	1004 ± 12	698.1 ± 3.3	0.01446 ± 0.00013	933 ± 8	**847 ± 16**	**1103 ± 16**	699.8 ± 3.3
HY1-11	55.25	837 ± 1	1523 ± 28	716.9 ± 3.2	0.01540 ± 0.00013	983 ± 9	**894 ± 18**	**1056 ± 18**	718.8 ± 3.2
HY1-12	63	681 ± 1	877 ± 4	858.9 ± 3.5	0.01804 ± 0.00020	1062 ± 12	**985 ± 15**	**966 ± 15**	861.4 ± 3.5
HY1-13	71.25	669 ± 1	428 ± 12	844.9 ± 4.4	0.01906 ± 0.00016	1133 ± 10	**1065 ± 11**	**885 ± 11**	847.6 ± 4.4
HY1-14	85	713 ± 1	1528 ± 4	798.8 ± 3.4	0.02027 ± 0.00020	1234 ± 12	**1142 ± 21**	**808 ± 21**	801.5 ± 3.4
HY2									
HY2-1	3.25	696 ± 1	1842 ± 13	773.0 ± 3.9	0.01908 ± 0.00015	1181 ± 10	**1079 ± 24**	**871 ± 24**	775.5 ± 3.9
HY2-2	6.5	690 ± 2	6088 ± 18	714.6 ± 3.5	0.02067 ± 0.00043	1322 ± 28	**1116 ± 80**	**834 ± 80**	717.0 ± 3.5
HY2-3	24.25	741 ± 1	6530 ± 24	728.9 ± 3.8	0.02057 ± 0.00027	1306 ± 17	**1100 ± 76**	**850 ± 76**	731.2 ± 3.9
HY2-4	37.25	743 ± 1	3672 ± 20	767.1 ± 3.8	0.02106 ± 0.00030	1308 ± 19	**1169 ± 45**	**781 ± 45**	769.7 ± 3.9
HY2-5	50.25	853 ± 2	2565 ± 14	768.0 ± 4.3	0.02150 ± 0.00021	1335 ± 13	**1227 ± 28**	**723 ± 28**	770.8 ± 4.3
HY2-6	84	806 ± 2	4791 ± 12	799.1 ± 3.3	0.02480 ± 0.00035	1511 ± 22	**1358 ± 53**	**592 ± 53**	802.3 ± 3.3
HY2-7	114.5	649 ± 1	4093 ± 10	777.2 ± 3.0	0.02746 ± 0.00038	1695 ± 24	**1535 ± 57**	**415 ± 57**	780.7 ± 3.1
HY2-8	129	721 ± 2	1848 ± 4	771.5 ± 3.5	0.02803 ± 0.00025	1736 ± 16	**1637 ± 26**	**313 ± 26**	775.2 ± 3.5
HY2-9	163	647 ± 1	2617 ± 6	758.2 ± 3.1	0.03002 ± 0.00034	1874 ± 22	**1750 ± 40**	**200 ± 40**	762.1 ± 3.2
HY2-10	193.5	786 ± 2	2715 ± 6	764.9 ± 3.4	0.03094 ± 0.00027	1925 ± 17	**1811 ± 33**	**139 ± 33**	769.0 ± 3.4
HY3									
HY3-1	23	187 ± 0	9616 ± 42	658.6 ± 3.7	0.00808 ± 0.00054	548 ± 33	**–419 ± 457**	**2369 ± 457**	657.9 ± 3.8
HY3-2	88.5	331 ± 1	2656 ± 14	652.6 ± 3.2	0.00957 ± 0.00020	634 ± 13	**434 ± 72**	**1516 ± 72**	653.5 ± 3.2
HY3-3	119	363 ± 1	35304 ± 212	646.9 ± 2.4	0.01488 ± 0.00109	990 ± 73	**–797 ± 876**	**2747 ± 876**	645.6 ± 2.9
HY3-4	145	373 ± 1	3777 ± 11	658.7 ± 3.3	0.01301 ± 0.00055	857 ± 36	**623 ± 96**	**1327 ± 96**	660.0 ± 3.4

The errors are 2σ errors. Decay constant values are: λ_{230} = 9.1577×10^{-6}/yr, λ_{234} = 2.8263×10^{-6}/yr (Cheng *et al.*, 2000) and λ_{238} = 1.55125×10^{-10}/yr (Jaffey *et al.*, 1971). Corrected ^{230}Th ages assume the initial $^{230}Th/^{232}Th$ atomic ratio of 4.4 ± 2.2×10^{-6}. Depths along the growth axes are relative to the top (youngest surface) of the stalagmites. Year BP: year before present (AD 1950).

test'. Briefly, they are (i) that $\delta^{18}O$ remains constant along a single growth layer, and (ii) there is no correlation between $\delta^{18}O$ and $\delta^{13}C$ along a growth layer. Another rigorous test for isotopic equilibrium conditions is the 'replication test' (Dorale *et al*., 1998; Hendy and Wilson, 1968; Wang *et al*., 2001). This involves the comparison of two or more speleothem records from different caves or from different locations within the same cave that grew contemporaneously. Considering the different conditions experienced by speleothems collected from different locations, such as flow paths, drip rates, CO_2 partial pressures, residence times, and degassing histories, it is unlikely that they would exhibit matching isotopic records if kinetic processes had occurred (Dorale *et al*., 1998).

Here, we used a combination of the Hendy test and the replication test to confirm that $\delta^{18}O$ equilibrium had been maintained over the growth history of the stalagmites. No significant changes in coeval $\delta^{18}O$ and $\delta^{13}C$ were observed (Figure 4). The $\delta^{18}O$ variations in the HY2 record essentially replicated those in the HY1 record during contemporaneous growth periods (AD 760–878) (Figure 5). The $\delta^{18}O$ records of HY1 and HY2 passed the Hendy test and replication test, indicating that no kinetic fractionation or water–rock interactions were likely to have had large effects on HY1 or HY2. Therefore, the oxygen isotopic signals of HY1 and HY2 are interpreted as primarily reflecting climate variations.

The similar contemporaneous trends and peaks for the $\delta^{18}O$ records of HY1 and HY3 are shown in Figure 5, with only some exceptional discrepancies, which are probably attributable to dating errors (Table 1). This suggests that the oxygen isotopes of HY3 formed under equilibrium conditions, and confirms again the isotopic equilibrium conditions of HY1.

Only a trivial difference of 0.2‰ was observed for the contemporaneous $\delta^{18}O$ segments of the HY1 and HY2 records in the period AD 760–880 (Figure 5). However, an offset of 1.1‰ occurs between the HY1 and HY3 $\delta^{18}O$ records (Figure 5). Similar systematic differences between coeval stalagmite $\delta^{18}O$ records in the same cave have been reported in the literature (e.g. Baker *et al*., 1997; He *et al*., 2005; Vollweiler *et al*., 2006; Wang *et al*., 2001). These discrepancies may be attributable to prior calcite precipitation in different water flow paths above the speleothems (Fairchild *et al*., 2006). The slow calcite precipitation processes could still keep isotopic equilibrium prevailed (Bar-Matthews *et al*., 1996). If this were not the case, the $\delta^{18}O$ values for HY1, HY2, and HY3 would not exhibit consistent variations during their contemporaneous growth periods.

Composite stalagmite HY $\delta^{18}O$ record

To generate a composite record for the last 1860 years from the three stalagmites, we adjusted the $\delta^{18}O$ offsets to the HY2 (0.2‰) and HY3 (1.1‰) records on the level of HY1. The HY1 record and the adjusted HY2 and HY3 records were then combined to construct a new record. The new record was composed of (i) the HY3 record from AD 1308 to the present (adjusted to the level of HY1), (ii) the original HY1 record between AD 760 and 1305, and (iii) the HY2 record between AD 138 and 754 (adjusted to the level of HY1). Finally, the new record was normalized and a composite Huangye $\delta^{18}O_R$ record was generated. As shown in Figure 5, the composite record reproduces the variations in the three original records.

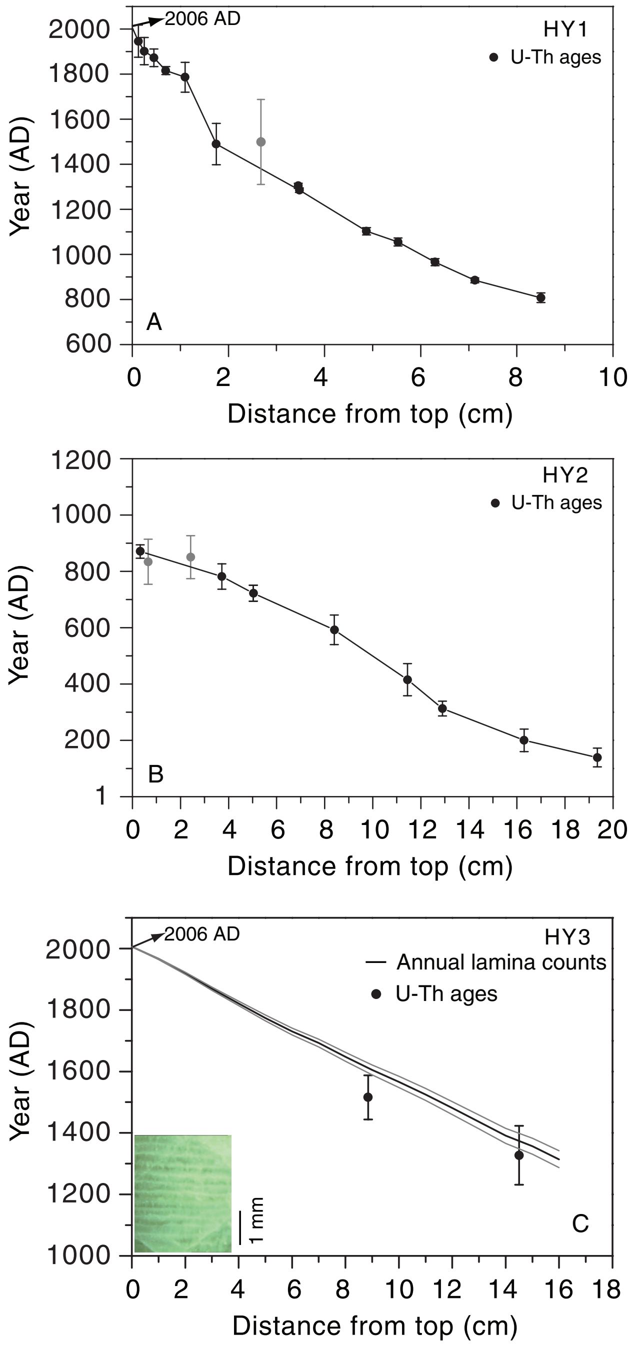

Figure 3. Age models for the Huangye Cave stalagmites. Linear interpolation methods with ^{230}Th dates were used for stalagmites HY1 (A) and HY2 (B). The ^{230}Th dates with large errors (grey symbols) were excluded. An age model constructed by counting annual laminae, supported by ^{230}Th dates, was used for HY3 (C) (see text for details). The black line in panel C represents the annual lamina counts and the grey lines represent a ±4% error applied to the lamina counts. Inset image shows well-developed annual laminae

Climate variations revealed by stalagmite $\delta^{18}O$ records

A previous study of the Wanxiang Cave (33°19′N, 105°00′E, 1200 m a.s.l.) in eastern Gansu Province (Zhang *et al*., 2008) suggested that temperature has little effect on the δ^{18}O of stalagmite calcite in this area, when both the temperature dependence of δ^{18}O fractionation in calcite-water (about −0.24‰/°C, O'Neil *et al.*, 1969) and the temperature dependence of δ^{18}O in precipitation (no greater than 0.24‰/°C, Johnson and Ingram, 2004) are considered. The δ^{18}O variations in the stalagmites from this area are mainly controlled by the 'amount effect', which induces δ^{18}O variations in meteoric water (see figure S4 of Zhang *et al*., 2008). Because the precipitation above the Huangye Cave comes mainly from the Asian summer monsoon, we interpreted the δ^{18}O variations in the stalagmites from the Huangye Cave as reflecting changes in the Asian summer monsoon precipitation. High summer monsoon precipitation in this area results in lower δ^{18}O values in the average annual precipitation and ultimately reduces the $^{18}O/^{16}O$ ratio in stalagmites, and *vice versa*.

The composite Huangye $\delta^{18}O_R$ record, with a resolution of 2–7 years, shows substantial variability in the monsoon precipitation over the past 1860 years (Figure 5D). The monsoon precipitation generally declined from AD 138 to 600, and then increased to a maximum in AD 850. After AD 850, the monsoon precipitation decreased gradually, until a sharp increase between AD 1050 and 1140. From AD 1140 to 1360, the monsoon precipitation declined again, with substantial decadal- to centennial-scale fluctuations. After AD 1360, the monsoon precipitation remained low, with some occasional high decadal-scale values, until a sharp increase between AD 1850 and 1870. The last major feature was a distinct decline in monsoon precipitation at the end of the twentieth century.

Three notable wet periods are recorded in the Huangye record: AD 138–450, AD 730–1200, and AD 1860–1960 (Figure 5D). The composite record illustrates a remarkably dry period in AD 1530–1860, which corresponds to the 'Little Ice Age' (LIA) in Europe (Bradley and Jones, 1992; Lamb, 1965). The other short dry period was in AD 1320–1410.

Comparison with different precipitation records

Comparison of the Huangye $\delta^{18}O_R$ record with the Wanxiang δ^{18}O record showed a remarkable resemblance (Figure 6A). The significant positive correlation ($R = 0.44$, $P < 0.001$) between the two records over the past 1810 years indicates the validity of the two proxy precipitation records in the same region. The only discrepancy between the two time series occurs at AD 530–660, which is probably attributable to different growth rates and dating errors for the stalagmites from the two caves.

Tan *et al*. (2008) reconstructed the variations in precipitation in Longxi, ~130 km northwest of the Huangye Cave, since AD 960 using the drought/flood (D/F) index inferred from historical documents (an increased D/F index represents reduced precipitation). Recently, this reconstruction was extended to the most recent 2000 years (Tan *et al*., 2010). Because the D/F index is estimated with a five-class classification method (wet, slightly wet, normal, slightly dry, and dry), which is mainly based on the time of occurrence, the affected area, and the degree of drought and flood in spring, summer, or autumn (Zhang, 1983), it does not reflect the linear trend in precipitation variability over the past 2000 years. To better compare our data with the Longxi D/F index record, we removed the linear trend in the Huangye $\delta^{18}O_R$ record using a linear regression model. As shown in Figure 6B, the detrended Huangye record showed strong similarity to the Longxi record, which confirms the climatic interpretations of the Huangye and Wanxiang records and supports the precipitation–cave δ^{18}O relationship in this area.

The analysis of a daily rainfall data set from China from 1961 to 2000 showed a decreasing trend in precipitation over the mid-lower Yellow River Basin (Qian and Lin, 2005). Zheng *et al.* (2005) reconstructed the precipitation variations in the four subregions of the mid-lower Yellow River Basin for the last 300 years,

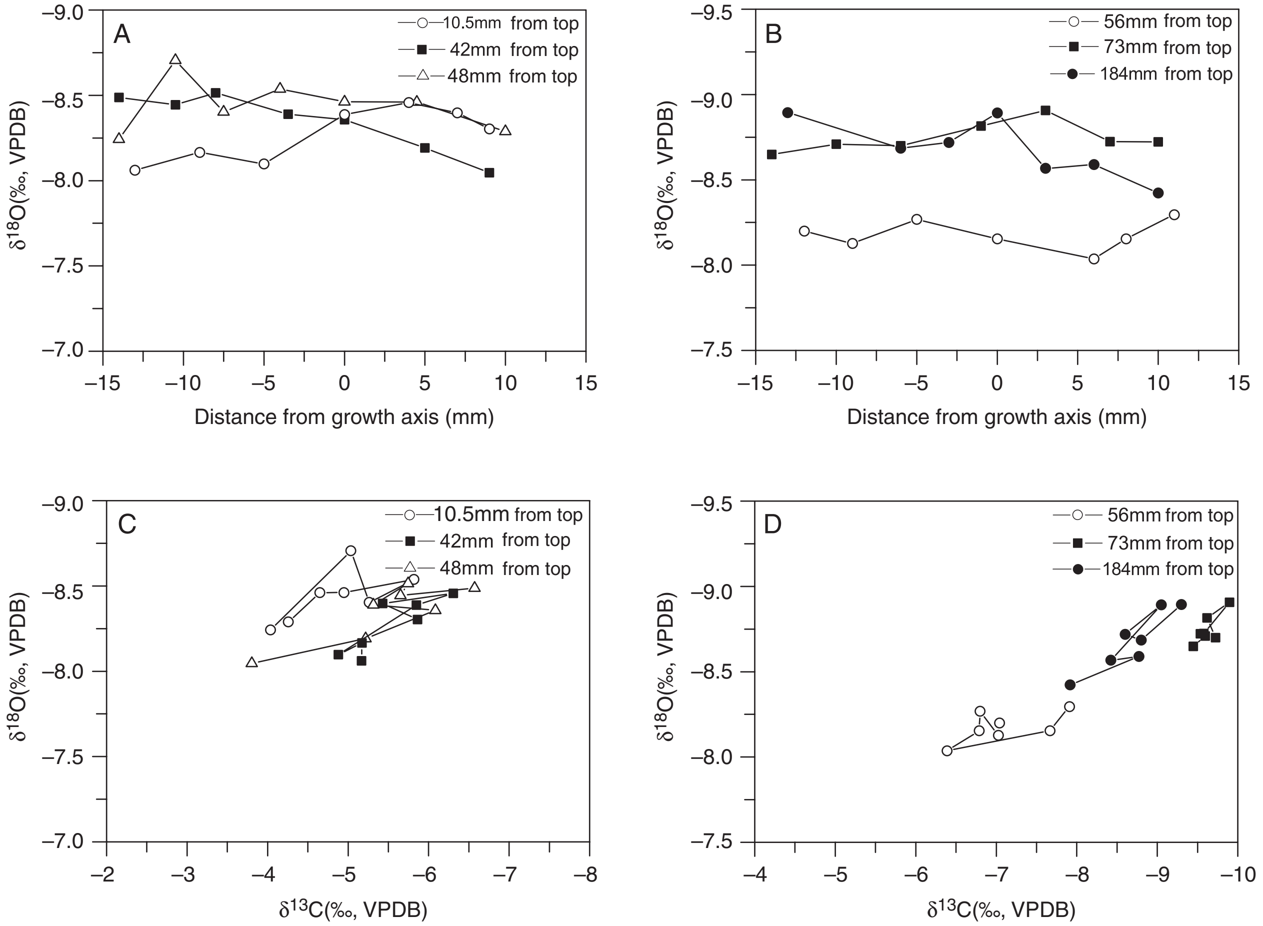

Figure 4. Hendy test on three horizons of stalagmite samples HY1 and HY2. Coeval $\delta^{18}O$ data for (A) HY1 and (B) HY2. $\delta^{18}O$ versus $\delta^{13}C$ plots for (C) HY1 and (D) HY2

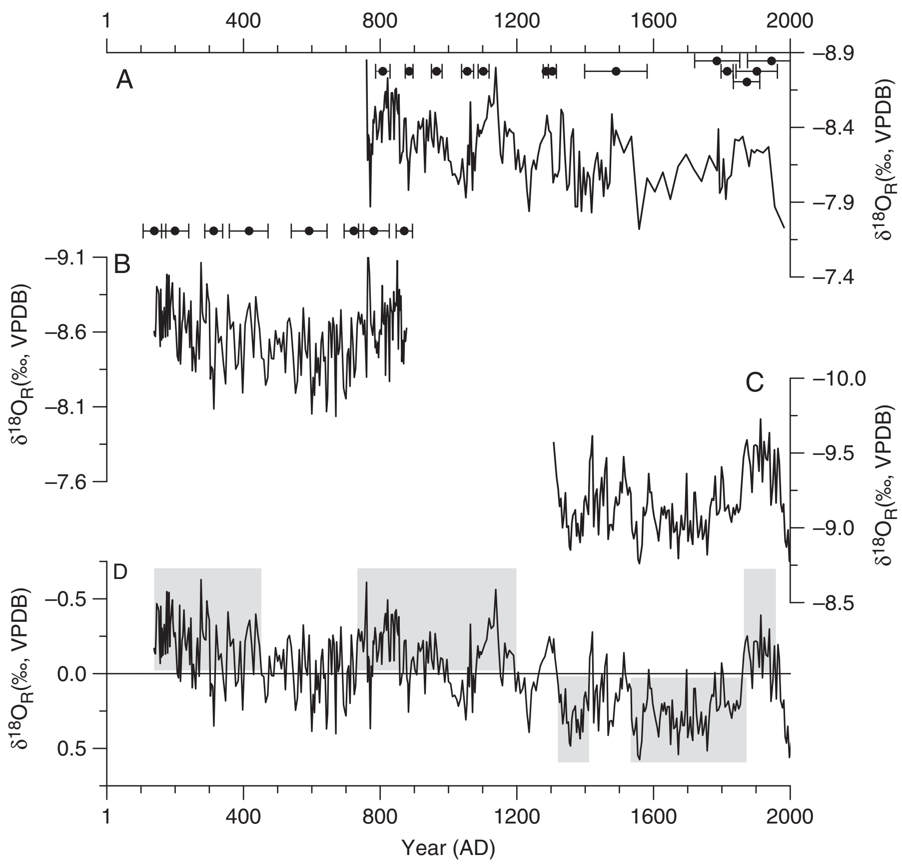

Figure 5. Oxygen isotopic records for stalagmites (A) HY1, (B) HY2, and (C) HY3 from the Huangye Cave. ^{230}Th ages of HY1 and HY2 with errors are shown. (D) The composite relative $\delta^{18}O$ ($\delta^{18}O_R$) record derived from the records of HY1, HY2, and HY3 (see text for details)

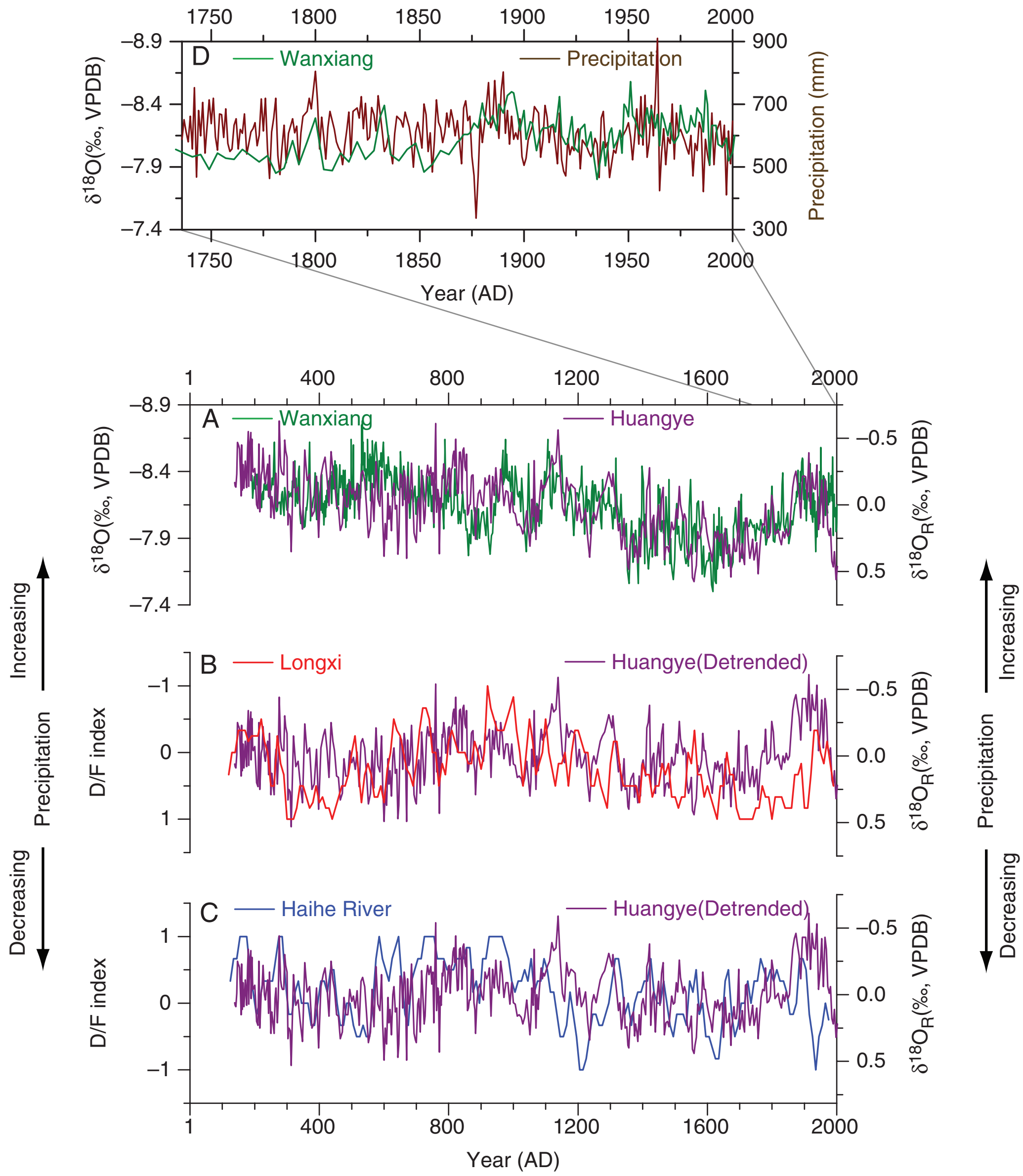

Figure 6. Comparison of the Huangye $\delta^{18}O_R$ record (magenta line) with other precipitation records in the semi-humid region of northern China: (A) Wanxiang $\delta^{18}O$ record (green line; Zhang *et al*., 2008); (B) drought/flood (D/F) index record of the Longxi area (three-point running means, with increased D/F index representing decreased precipitation (red line; Tan *et al*., 2008, 2010)); (C) D/F index record for the Haihe River Basin (three-point running means, with increased D/F index representing increased precipitation (blue line; Yan *et al*., 1993)); (D) comparison of the Wanxiang $\delta^{18}O$ record (green line; Zhang *et al*., 2008) with the average precipitation record for the mid-lower Yellow River Basin (puce line; Zheng *et al*., 2005)

based on the snow and rainfall records in historical documents. The precipitation records show region-wide synchronous variations over the mid-lower Yellow River Basin on a decadal-scale during the last 300 years.

We compared the precipitation record for eastern Gansu Province with that for the mid-lower Yellow River Basin. Because the temporal resolution of the Wanxiang record is higher than that of the Huangye record in the last 1000 years and the two records exhibit a remarkable resemblance (Figure 6A), the Wanxiang $\delta^{18}O$ record was chosen for a comparison with the average precipitation record of the mid-lower Yellow River Basin (Zheng *et al*., 2005). As shown in Figure 6D, the two records correlate well. For example, both of them record precipitation peaks at around AD 1800, AD 1890, and AD 1970. We further compared the detrended Huangye $\delta^{18}O_R$ record with a 2000-year precipitation record, which was reconstructed from historical documents using the D/F index (an increase in the D/F index is defined as representing increased precipitation), in the Haihe River Basin (Yan *et al*., 1993) (Figure 6C). The close similarity between these suggests that the precipitation variability was synchronized over the semi-humid region of northern China on decadal to centennial scales during the last 1860 years.

Climate changes and their influences on societal evolution

Numerous studies have suggested that climate changes have had important effects on societal evolution (e.g. Cowie, 1998; deMenocal *et al*., 2000; Hsu, 1998; Liu *et al*., 2009; Núñez *et al*., 2002; Weiss and Bradley, 2001; Yancheva *et al*., 2007; Zhang *et al*., 2008). We counted the numbers of conflicts and wars in northern China during historical periods (Editing Committee of China's Military History (ECCMH), 1985; Wang, 2007) and compared them with the variations in precipitation revealed by the Huangye $\delta^{18}O_R$ record and the average temperature variations in

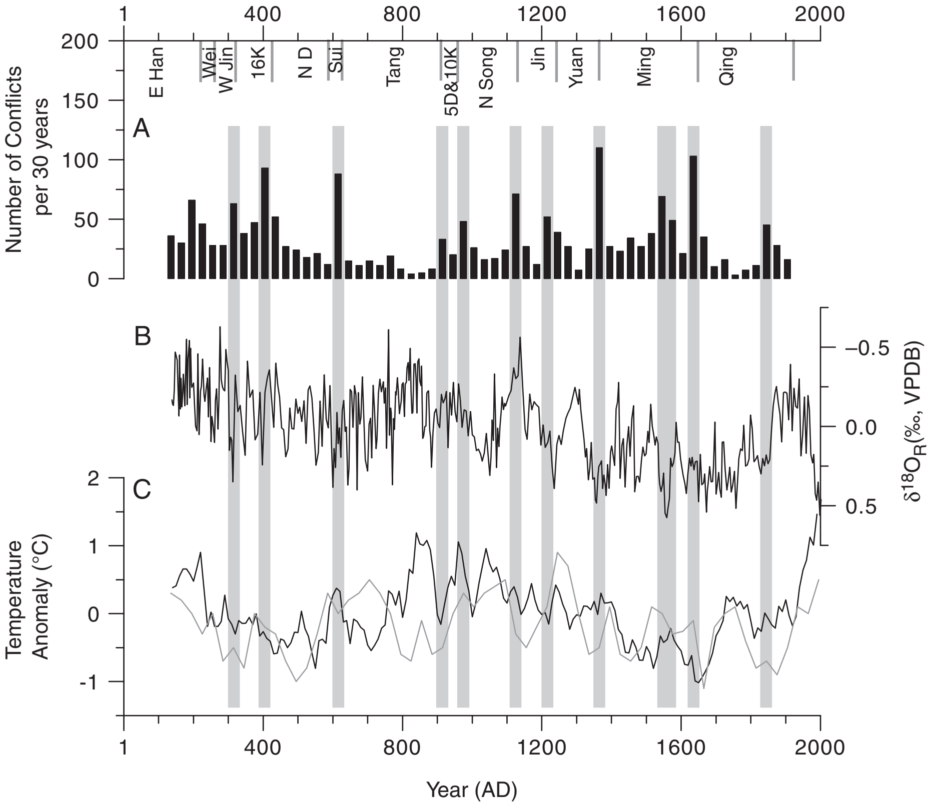

Figure 7. Comparison of climate change and warfare. (A) The number of conflicts and wars that occurred in northern China (ECCMH, 1985; Wang, 2007). (B) The precipitation variations in semihumid northern China revealed by the Huangye $\delta^{18}O_R$ record. (C) The average temperature variations in China (black line; Yang *et al.*, 2002), and the winter-half-year temperature variations in eastern China (grey line; Ge *et al.*, 2003). The ancient dynasties that controlled northern China in the last 2000 years are indicated. E Han, the Eastern Han Dynasty period; W Jin, the Western Jin Dynasty period; 16K, the 16 kingdoms period; N D, the Northern Dynasty period; 5D&10K, the Five Dynasties and Ten Kingdoms period; and N Song, the Northern Song Dynasty period

China (Ge *et al*., 2003; Yang *et al*., 2002). As shown in Figure 7, almost all the peak periods of warfare in dynastic transition times corresponded to sharp declines in precipitation or/and temperature. For example, there were up to 110 conflicts and wars in northern China between AD 1351 and 1380 (the period between the end of the Yuan Dynasty and the beginning of the Ming Dynasty). At that time, a great drought was recorded in the Huangye record and a sharp decline in temperature was also recorded in Chinese historical documents (Ge *et al*., 2003). The peak period of warfare between AD 601 and 630 (the period between the end of the Sui Dynasty and the beginning of the Tang Dynasty) corresponds to the driest time in the previous millennium. The peak period of warfare at the end of the Ming Dynasty corresponds to the dry/cold climate of the LIA. It seems that the peak period of warfare between AD 1111 and 1140 corresponds to the precipitation peak in the Huangye record. However, when the Huangye record is checked against the Wanxiang (Zhang *et al*., 2008) and Longxi (Tan *et al*., 2008) records, we think the out-of-phase relationship may be caused by dating errors in the Huangye record. Therefore, the peak period of warfare between AD 1111 and 1140 probably corresponds to the sharp decline in precipitation at ~ AD 1145 in the Huangye record.

Although many political, economic, and military factors can provoke conflicts and wars, the influence of climatic deterioration cannot be ignored (Liu *et al*., 2009; Wang *et al*., 1996; Weiss and Bradley, 2001). The rain-fed agricultural harvest in the semi-humid region relies heavily on climatic conditions (Wang *et al*., 2005). Dry/cold climate in the semi-humid region could lead to crop failure, resulting in famine, which may cause uprisings and ultimately wars (Bryson and Murray, 1977; Hinsch, 1988; Hsu, 1998; Wang *et al*., 2005). At the same time, climatic deterioration could cause pasture areas to extend south, resulting in nomadic migrations and invasions (Hinsch, 1988; Man *et al*., 2000; Ni, 1988; Wang, 1996), which may also provoke conflicts and wars. The crop failure and the chaos of war in the semi-humid region of northern China may destroy the economy, resulting in massive numbers of deaths and the southward migration of the population (Wang, 1996). The worsening economic situation and the depopulation of semi-humid northern China, one of the core domination areas of the ruling dynasty and where the capital was located, may cause a reduction in military expenditure and conscription resources, weakening the military strength of the ruling dynasty (Wang *et al*., 1996). This sustained increasing of conflicts and wars and weakening of military strength may constitute a double strike against the ruling dynasty, and may further cause its collapse. However, climatic deterioration should not be considered the only reason for the collapse of the ruling dynasty. Many dry events also occurred in the mid-Tang Dynasty period, the mid-Northern Song Dynasty period, and the mid-Qing Dynasty period, which correspond to periods of few conflicts and wars (Figure 7). Not only did the climatic deterioration in the semi-humid region of northern China cause destruction, it also sometimes promoted the development of southern China. For example, advanced technology was brought to southern China by emigrants from northern China at the end of the Tang and Northern Song Dynasties, accelerating the development of southern China (Lan, 2007; Ni, 1988; Zheng, 1996).

Conclusions

We used the $\delta^{18}O$ series of three stalagmites from the Huangye Cave in eastern Gansu Province, northern China, to construct a precisely dated, continuous $\delta^{18}O$ record for the last 1860 years. The Hendy test and replication test indicated that the three stalagmites were deposited under isotopic equilibrium conditions. We ascribed the primary cause of these $\delta^{18}O$ variations to the variability in monsoon precipitation. The Huangye record replicates the variations in the Wanxiang record (Zhang *et al*., 2008), and is also very similar to the precipitation record reconstructed from historical documents in this area (Tan *et al*., 2008, 2010).

The inferred monsoon precipitation variations in eastern Gansu Province correlate well with those in the mid-lower Yellow River Basin (Zheng *et al*., 2005) and the Haihe River Basin (Yan *et al*., 1993), suggesting synchronous precipitation variability over the semi-humid region of northern China on decadal to centennial scales during the late Holocene. A comparison of climate change and warfare patterns shows that almost all the peak periods of warfare in dynastic transition times correspond to sharp declines in precipitation or/and temperature in semi-humid northern China, indicating a strong connection between climate and culture. Our study suggests that climatic deterioration in semi-humid northern China could have played an important role in Chinese societal evolution.

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