A Chinese cave links climate change, social impacts, and human adaptation over the last 500 years

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The collapse of some pre-historical and historical cultures, including Chinese dynasties were presumably linked to widespread droughts, on the basis of synchronicities of societal crises and proxy-based climate events. Here, we present a comparison of ancient inscriptions in Dayu Cave from Qinling Mountains, central China, which described accurate times and detailed impacts of seven drought events during the period of 1520–1920 CE, with high-resolution speleothem records from the same cave. The comparable results provide unique and robust tests on relationships among speleothem δ18O changes, drought events, and societal unrest. With direct historical evidences, our results suggest that droughts and even modest events interrupting otherwise wet intervals can cause serious social crises. Modeling results of speleothem δ18O series suggest that future precipitation in central China may be below the average of the past 500 years. As Qinling Mountain is the main recharge area of two large water transfer projects and habitats of many endangered species, it is imperative to explore an adaptive strategy for the decline in precipitation and/or drought events.

In recent years, increasing attention is paid to the impact of climate change and adaptation strategies. It is evident that climate change could pose critical impact on ecosystems and society. For instance, rainfall amount deviations directly affect agricultural crop yields, forest advance and retreat, and human health. In particular, drought events have widely occurred on various timescales and in turn played an important role in changing social stability and human welfare during pre-historical and historical times. Collapses of many ancient civilizations, such as the Neolithic culture in north central China, the Akkadian Empire, pyramid-constructing Old Kingdom civilization of Egypt and classic Maya, have all been linked to intense droughts during mid- and late Holocene, on the basis of apparent synchronicities between proxy-inferred drought events and historically documented societal crises.

In the past decade, stalagmite δ18O records from China have characterized many aspects of the Asian monsoon variability over the past 500 ka years on centennial to orbital scales. These records also show a possible linkage between climate change and the demise of several Chinese dynasties during the last 1800 years, such as Tang, Yuan and Ming Dynasties. However, the relationship between Chinese stalagmite δ18O variations, monsoon climate change, and social crises is still in dispute, and more evidence is required to evaluate the impact of past climate change.

Dayu Cave (33°08′ N, 106°18′ E, 870 m a. s. l.) is located on the southern slope of the Qinling Mountains, central China, and is more than 2 km long (Fig. 1). The cave has a high relative humidity...
 (>97%) and high CO₂ concentration (1600 ppm in the central pathway on 22 September, 2009). The cave temperature is 13.0 °C, consistent with the local annual mean temperature (12.9 °C). Climate in this region is dominated by the Asian monsoon system, with a mean annual rainfall of 1100 mm of which >70% are received during the summer monsoon months (June-October) (Fig. S1). Monitoring of precipitation above the cave between June 2010 and May 2011 shows that the δ¹⁸O of precipitation is lower during summer monsoon seasons (Fig. S2). Water balance analysis at the cave site indicates that most water surplus occurs between July and October (Fig. S1). Recharge of the aquifer thus occurs mainly during summer monsoon seasons. Spatial correlation analysis indicates that precipitation changes at the cave are positively correlated with those in central China (Fig. S3).

Results
Many ancient inscriptions were disclosed in Dayu Cave, which indicate that local ancient people visited the cave frequently, at least 70 times during 1520–1920 CE. According to the inscriptions, seven major drought events were clearly described, occurring in 1528 CE, 1596 CE, 1707 CE, 1756 CE, 1839 CE, 1891 CE and 1894 CE (Fig. 2), respectively. These inscriptions described many details of the droughts (Table 1). For example, one of them (Fig. 2A) stated: “On May 24th, 17th year of the Emperor Guangxu period, Qing Dynasty [the traditional Chinese calendar, equivalent to June 30th, 1891 CE], the local mayor, Huaizong Zhu led more than 200 people into the cave to retrieve water. A fortuneteller named Zhenrong Ran prayed for rain during a ceremony.” Three years later in 1894 CE (June 12th, 20th year of the Emperor Guangxu period, Qing Dynasty), another drought event occurred. The same mayor and fortuneteller again led more than 120 people into the cave to collect water (Fig. 2B). Another inscription indicated that “On June 8th, 46th year of the Emperor Kangxi period, Qing Dynasty [July 7th, 1707 CE], the governor of Ningqiang district came to the cave to pray for rain.”
Figure 2. Photos of ancient inscriptions inside Dayu Cave, which recorded seven drought events. The yellow and red panels mark dates and the descriptions of drought events, respectively. All photos were taken in Dayu Cave by L. Tan.
The seven drought events described in the inscriptions are notably reflected in the stable isotopic and trace elemental records of a stalagmite DY1 from the Dayu cave (Fig. 3). DY1 was collected about 1 km from the cave entrance, covering the period from ca. 1265 to 1982 CE continuously (Fig. S4, Table S1). The initial low-resolution $\delta^{18}O$ results from DY1 stalagmite were reported in 200919. Here we built a more solid age model with additional six $^{230}$Th dates and a higher resolved (~1.3 yrs) stable isotopic and trace elemental profiles capturing annual $\delta^{18}O$, $\delta^{13}C$ (Table S2) and Sr/Ca ratio variations during the last 500 years.

"Hendy test"20 results show that both the $\delta^{18}O$ and $\delta^{13}C$ remain constant along growth layers of DY1 (Fig. S5). Some limitations of "Hendy test" were reported. For example, the isotopic equilibrium could theoretically occur in the center of the speleothem at the same time that kinetic fractionation occurs at the flanks21. However, the stalagmite was most likely deposited at isotopic equilibrium conditions, if the isotopic values remain constant along growth layers. In addition, the DY1 $\delta^{18}O$ record is similar to a calcite stalagmite SF1 ($r=0.21$, $N=393$, $p<0.001$) from the Buddha Cave in the southern Qinling Mountains22, 300 km northeast of the Dayu Cave-authors) came to the cave to get water (other details are illegible-authors).

| Droughts | Solar calendar dates | Descriptions |
|----------|----------------------|--------------|
| 1        | 1528 CE              | Drought occurred in 7th year of the Emperor Jiajing period, Ming Dynasty (the traditional Chinese calendar-authors). Gui Jiang and Sishan Jiang came to Da'an town (the town where Dayu Cave is located-authors) to acknowledge the Dragon Lake inside in Dayu Cave. |
| 2        | July 27th, 1596 CE   | On July 3rd, 24th year of the Emperor Wanli period, Ming Dynasty, local people came to the cave to get water because of the big drought (their name are omitted here-authors). |
| 3        | July 7th, 1707 CE    | On June 8th, 46th year of the Emperor Kangxi period, Qing Dynasty, the governor of Ningqiang district came to the cave to pray for rain. |
| 4        | June 6th, 1756 CE    | On May 9th, 21th year of the Emperor Qianlong period, Qing Dynasty. 17 scholars came to the cave to pray for rain (their name are omitted here-authors). |
| 5        | July 27th, 1839 CE   | On June 17th, 19th year of the Emperor Daoguang period, Qing Dynasty, 120 persons from Laeyang county (a county in the north of Dayu Cave-authors) came to the cave to get water (other details are illegible-authors). |
| 6        | July 30th, 1891 CE   | On May 24th, 17th year of the Emperor Guangxu period, Qing Dynasty, the local mayor, Huaiyong Zhu led more than 200 people into the cave to get water. A fortuneteller named Zhenrong Ran prayed for rain during a ceremony. |
| 7        | June 14th, 1894 CE   | Drought lasted for more than one month. On June 12th, 20th year of the Emperor Guangxu period, Qing Dynasty, scholar Peilan Zheng, mayor Huaiyong Zhu, heads of the clan Wenxin Zheng and Bangyun Zheng, and Zhenrong Ran, Hengyu Zhu, led more than 120 persons to the cave to get water. |

Table 1. Seven drought events recorded in the ancient inscriptions inside Dayu Cave during the period of 1500–1920 CE.

The seven drought events described in the inscriptions are notably reflected in the stable isotopic and trace elemental records of a stalagmite DY1 from the Dayu cave (Fig. 3). DY1 was collected about 1 km from the cave entrance, covering the period from ca. 1265 to 1982 CE continuously (Fig. S4, Table S1). The initial low-resolution $\delta^{18}O$ results from DY1 stalagmite were reported in 200919. Here we built a more solid age model with additional six $^{230}$Th dates and a higher resolved (~1.3 yrs) stable isotopic and trace elemental profiles capturing annual $\delta^{18}O$, $\delta^{13}C$ (Table S2) and Sr/Ca ratio variations during the last 500 years.

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There is a significant negative correlation between the DY1 $\delta^{18}O$ and the annual rainfall during the period between ~1957 and 1982 CE ($r=-0.44$, $N=24$, $p<0.05$). The correlation coefficient is not very
The δ18O values may correspond to reduced precipitation, and vice versa (Fig. S7). During the last 500 years, the notable positive excursions in δ18O coincided with the droughts documented in the inscriptions, corroborating a generally inverse relationship between rainfall amount (mainly from summer monsoon) and speleothem δ18O in this region.

The δ13C values are relatively higher during each drought event in the last 500 years too (Fig. 3). In fact, there is a significant positive correlation (r = 0.37, P < 0.01, N = 393) between the δ13C and the δ18O records of DY-1 during 1500–1982 CE (Fig. S8). Speleothem δ13C values have bedrock, atmospheric, and soil gas sources. As a result, many factors may affect the speleothem δ13C variations, including: (1) the fracture of epikarst zone and difference of lattice work in vadose zone (open/closed systems), (2) the extent of dissolution of the host rock, (3) the overlying vegetation types and density, (4) the microbial activity in the overlying soil, (5) prior precipitation of calcite (PCP) in the epikarst zone, (6) and the evaporation and degassing of drip water. The constant temperature inside Dayu Cave suggests it is

Figure 3. Comparison of drought events recorded in the inscriptions with speleothem δ18O, δ13C and Sr/Ca records in Dayu Cave during the last 500 years. The black triangles indicate 70 visits recorded in the cave, with some occurred in the same year. The orange squares indicate seven historical drought events occurred in 1528 CE, 1596 CE, 1707 CE, 1756 CE, 1839 CE, 1891 CE and 1894 CE, respectively. (A) δ18O record of DY1 (dark green). The red line represents annual rainfall amount record from the Ningqiang meteorological station, 38 km south of Dayu Cave, during the period 1957–2000 CE, with a 3-year moving average. (B) Detrended Sr/Ca record of DY1 (light blue); (C) δ13C record of DY1 (purple). Black vertical bars show locations of 230Th dates, with errors of ±0.4 to ±4 years. The straight lines in panel A and C indicate the average δ18O (−7.19‰) and δ13C (−2.54‰) values of the entire series, respectively.
a closed system. Factors (3) and (4) are related to the vegetation change and climatic conditions. On decadal- to annual- time scales, cold and dry climate could reduce the vegetation cover and microbial activity, and result in higher δ13C values in speleothems. Factors (2) and (5) are related to hydrogeochemical processes in the epikarst zone and affected by climatic conditions. The increased residence time of the seepage water during drier conditions may allow more bedrock to be dissolved, favor PCP in the unsaturated zone, resulting in higher δ13C values in speleothem25–27. In addition, dry condition may enhance the evaporation and CO2 degassing of drip water28, and cause higher δ13C of speleothems in Dayu Cave.

As shown in Fig. 3, the droughts in 1596 CE, 1707 CE, 1756 CE, and 1839CE corresponded well with elevated Sr/Ca ratios. The other three droughts in 1528 CE, 1891 CE, and 1894 CE are also comparable with increased Sr/Ca ratios, considering age differences caused by different sampling intervals and paths. As discussed before, drier conditions could promote longer water residence times in the epikarst, decreased drip rates, and enhanced CO2 degassing into air voids within the unwetted epikarst. These conditions lead to Sr/Ca ratios higher than congruent bedrock dissolution due to preferential removal of Ca during PCP and increase the Sr/Ca ratio in speleothem29–31. The positive correlation between δ18O and Sr/Ca records of DY1 (r = 0.22, P < 0.01, N = 393) further confirm the observed inverse relationship between speleothem δ18O and rainfall amount in this region.

In summary, Dayu Cave provides for the first time an in situ comparison between historical drought events and speleothem records from the same cave. The in-phase variations in speleothem δ18O and Sr/Ca during droughts in the last 500 years demonstrate a convincing anti-correlation between rainfall amount and speleothem δ18O in this region25.

**Discussion**

**Impacts of climate change on local society.** Historical documents show that drought events recorded in Dayu Cave caused serious social problems. For example, the drought of 1528 CE led to “a big starvation and cannibalism”33 around the Qinling mountain region, from southern and central Shaanxi Province to eastern Gansu Province34. Droughts in the 1890s also caused severe starvation and triggered local social instability, which eventually resulted in a fierce conflict between government and civilians in 1900 CE35. A recent study suggested that the collapse of classic Maya civilization was caused by modest reduction in precipitation11,12. Similarly, comparisons between stalagmite δ18O changes and historical records inside Dayu Cave (Fig. 3) also provide robust evidence that even modest droughts during relatively wet periods had serious societal consequences. As shown in Fig. 3, the drought around 1596 CE was not very severe in comparison with others during the last 500 years in the Dayu δ18O record. However, in the context of the overall wet climate during 1530–1685 CE, the multi-year drought appears to be unusual and caused local societal unrest. The inscriptions (Fig. S9) describe the event as “mountains are crying due to drought”, and local people “came to the cave to get water” in July and August when the summer monsoon is presumably the strongest. The δ13C value of the stalagmite also reaches the highest value in the last 500 years in the drought in 1596 CE25.

As described in the inscriptions, in an attempt to adapt to droughts, people in the area came to the cave to obtain water and pray for rain. Likewise, during recent droughts in southwestern China, karst groundwater became a very important water source for local people. This demonstrates a common human adaptation to such climatic changes under similar conditions.

**Future climate change in southern Qinling Mountain region.** A time domain combined model16 was used here to evaluate potential future precipitation changes in the area on the basis of the Dayu δ18O series. The modeled δ18O series fits the original series before 1982 CE, and is then extrapolated for 60 years to 2042 CE (Fig. 4A). Strong coherence between the predicted δ18O series and the observed precipitation variations in the period of 1982–2012 CE further validate this approach (Fig. 4B). According to our predicted δ18O changes, precipitation between 1982 and 2042 CE will likely fall below the average over the past 500 years in central China. Two droughts, comparable with historical droughts, appear in the model: the 1990s and the late 2030s. Instrumental data confirm the first drought event in the 1990s (Fig. 4B).

Spectral analysis of the Dayu record yields significant periodicities at 96, 6.3, 3.4 and 2.8 years, with the 2.8, 3.4, and 6.3 year periods corresponding to the El Niño–Southern Oscillation (ENSO) cycle (Fig. 5A). Spatial correlation analysis also indicates that the precipitation in Dayu Cave region anti-correlates with the sea surface temperature (SST) of Niño 4 region during the period of 1960–2009 CE (Fig. 5B). Results of climate model simulations suggest that the tropical Pacific SST gradient decreases under conditions of global warming, resembling El Niño-like SST patterns37,38. If the current warming continues, precipitation may decrease in the cave region, which is consistent with our prediction.

Precipitation in the southern Qinling Mountain region is the main recharge of Danjiangkou Reservoir, which supplies water to the middle route of South-to-North Water Transfer Project in China. Recently, another large Hanjiang-to-Weihe River Water Transfer Project is under construction, and its water source is similarly recharged by precipitation in the southern Qinling Mountain region. In addition, Qinling Mountains are important refugia for many rare and endangered species including giant pandas (Ailuropoda melanoleuca)39. It is therefore crucial to explore an adaptive strategy to prepare for the possible future decline in precipitation and/or drought events in the region.
Methods

$^{230}$Th dating. Stalagmite DY1 was cut into halves along the growth axis and polished. Subsamples for $^{230}$Th dating were obtained by drilling along the growth axis of the stalagmites with a hand-held carbide dental drill. The chemical procedure used to separate uranium and thorium followed those described in ref. S1. Measurements of uranium and thorium were performed on inductively coupled plasma mass spectrometers (ICPMS), Thermo-Finnigan ELEMENT and Thermo Fisher NEPTUNE, following procedures described in ref. S2 and ref. S3, respectively. Corrections for initial $^{230}$Th were made assuming an initial $^{230}$Th/$^{232}$Th atomic ratio of $4.4 \pm 2.2 \times 10^{-6}$. A total of 15 $^{230}$Th dates were obtained for DY1 (Table S1). Two-sigma date errors are less than 4 years for 13 layers. Linear interpolations between $^{230}$Th dates were used to establish the chronology (Fig. S4).

Stable isotope and trace elements analyses. We performed stable isotope analyses ($\delta^{18}$O and $\delta^{13}$C) for DY1 at intervals from 100$\mu$m to 250$\mu$m, depending on growth rate. All subsamples were analyzed on an on-line, automated carbonate preparation system (Kiel III) linked Finnigan MAT-252 gas source mass spectrometer (Table S2). International standard NBS19 and inter-laboratory standard TTB1 were measured every 10–15 samples. Arbitrarily selected duplicates were conducted to check the homogeneity and reproducibility. Stable isotopic values reported are relative to the Vienna PeeDee Belemnite (VPDB) standard. The standard results show that precisions of $\delta^{18}$O and $\delta^{13}$C analysis are better than
0.1‰ (2σ). Sr and Ca counts of the stalagmite were measured using the Itrax core scanner at the First Institute of Oceanography, State Oceanic Administration at 0.1 mm resolution.

The prediction model. The DY1 δ¹⁸O series was decomposed to determine the significant harmonics and their corresponding periodicities (ref. S4). Based on the cumulative variance contribution of ~90%, there were 82 significant harmonics. We then used an Auto Regressive And Moving Average [ARMA(p, q)] model to simulate the residual errors of the δ¹⁸O series, which were produced by subtracting period terms from the original series. According to the Bayesian information criterion, the degrees p and q of the ARMA model were selected as 2 and 3, respectively. By combining the periodic terms and the results of ARMA(p, q) model, the prediction model of the δ¹⁸O series was established36.

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Author Contributions

L.T., Y.C. and Z.A. conceived the project and wrote the first draft of the paper. H.C, R.L.E. and C.C.S. contributed to the $^{230}$Th dating. L.T. and H.Z. performed the stalagmite $\delta^{18}O$ and trace element analyses. Y.D. performed the prediction model. S.F.M.B. and Y.G. gave constructive suggestions. All authors discussed the results, edited and commented on the manuscript.

Additional Information

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