Phenological records in Guanzhong Area in central China between 600 and 902 AD as proxy for winter half-year temperature reconstruction

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Received January 12, 2016; accepted April 1, 2016; published online July 14, 2016

Abstract Phenological data obtained from historical documents constitute highly important ecological evidence for the pre-instrumental period, and can be used in analyzing climatic change in history. In this study, 87 phenological records about seasonality of non-biological events (e.g., first frost date), agriculture and ornamental plants (e.g., first flowering date) over 77 years were extracted from historical documents from the Sui and Tang dynasties in China to reconstruct the winter half-year (from October to next April) temperatures in the Guanzhong Area (located in central China) from 600 to 902 AD. Transfer functions between temperature and phenophases with significant correlations were established by using modern observation data. Temperatures from the study period were reconstructed by applying the transfer functions to historical phenological data. The reconstruction indicates that the winter half-year temperatures during 600–902 AD were 0.23°C higher than the reference period (1961–1990). The temperature changed with two distinct stages. During the 600s–800s, temperatures were approximately 0.38°C higher than at present but then temperatures decreased in the subsequent period (800–902 AD). These results are similar to ones from previous studies on the mean temperature and the divisions between warm and cold periods during the study period, though differences were found in the degree of warmth/coldness. This reconstruction provides a valuable contribution to a better understanding of climatic variability during the Sui and Tang dynasties in China.

Keywords Phenological records, Temperature reconstruction, Sui and Tang dynasties in China, Guanzhong Area in China

Citation: Liu Y C, Dai J H, Wang H J, Ye Y, Liu H L. 2016. Phenological records in Guanzhong Area in central China between 600 and 902 AD as proxy for winter half-year temperature reconstruction. *Science China Earth Sciences*, 59: 1847–1853, doi: 10.1007/s11430-016-5325-5

1. Introduction

Continuous instrumental temperature measurements across the world have only been available since 1861 (Houghton et al., 2001). For the pre-instrumental period, a major challenge in investigating climatic changes is the rarity of reliable meteorological measurements. For studies of climatic variability prior to 1861, only natural (e.g., ice cores, tree

rings, pollens, stalagmites, sediments) and man-made (historical documents) proxies are available.

Phenology is the study of recurring biological life cycle stages and the seasonality of non-biological events, especially their timing and relationships with weather and climate (Schwartz, 2003). Phenological data derived from historical documents contain important past climatic evidence that have been used to reconstruct long-term changes in climatic factors, mainly temperature. In Europe, time series of grape veraison and maturity, grain harvest and ice break-up have been adopted to reconstruct past temperature

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changes (Chuine et al., 2004; Meier et al., 2007; Etien et al., 2008; Kiss et al., 2011; Možný et al., 2012). In Japan, cherry blossom records have been used to reconstruct spring temperatures dating back to the medieval period (800–1400 AD) (Aono and Kazui, 2008; Aono and Saito, 2010).

Over the past thousand years in China, people have kept abundant historical records documenting their lives and times, creating a large body of documentary sources containing descriptive information about local phenological events, either direct or implied. Based on these historical documents, many studies have developed long-term phenological time series in China (Gong et al., 1984; Zhang et al., 2005; Zheng et al., 2012; Ge et al., 2014), providing a database for past climate change reconstructions. Zhu (1973) first used phenological records to estimate past temperature changes. Subsequently, Ge et al. (2003) reconstructed temperatures for the past 2000 years in the central region of eastern China primarily using phenological records. To date, more phenological records have been extracted from both historical documents and modern systematic observations. The phenological records on frosts and snows (Zheng et al., 2005; Hao et al., 2009; Ge et al., 2010) and ornamental plants (Zhang, 1999; Fang et al., 2005; Liu and Man, 2012) have often been used to reconstruct the temperatures of specific regions and periods in China.

Among the studies of temperature reconstruction in China, one research hotspot concerns temperature changes during the Sui and Tang dynasties (581–907 AD). There have been at least three viewpoints on this issue. The first view point was originally put forward by Zhu (1973) and was subsequently supported by Wu et al. (1998), Zhu et al. (1998) and Lan (2001). They believed that the entire period of the Sui and Tang dynasties was warmer than the present. The evidence supporting their viewpoint was that the plum and orange trees growing in Chang'an (referring to Xi'an, a city in Guanzhong Area) during the Sui and Tang dynasties were not adaptable to growing in present conditions in that area. However, Man (1998) argued that the distribution of orange trees could not be used as proxy data because the orange trees were taken care of by people living in the palace during that time. Thus, he came up with a second viewpoint: the temperature was warmer than the present before the 760s and turned colder afterwards. Recent studies (Ge et al., 2003; Ge et al., 2010) support this second viewpoint, though disputing the timing of the shifts from warm to cold periods. By combining multiple paleoclimate proxy records synthesized from ice cores, tree rings, lake sediments and historical documents, Yang et al. (2002) proposed a third viewpoint: it was relatively colder before the 800s and turned warmer afterwards. In summary, there are significant controversies on the characteristics of temperature changes during the Sui and Tang dynasties that can be attributed to the lack of sufficient evidence supporting the reconstructions. Therefore, more evidence for the Sui and Tang dynasties is needed to further investigate the temperature changes

during this period.

In this study, we collected a number of phenological records from historical documents for the period 600–902 AD in the Guanzhong Area of China. Then, transfer functions were calibrated according to the relationship between modern temperature and phenological data. Finally, the winter half-year (WH, referring to October to next April) temperatures in the historical period were obtained by introducing the phenological records to the respective transfer functions. We also discuss the uncertainties of reconstruction and compare our result with other studies. Our objectives are to answer the following two questions: (1) How warm/cold was the period 600–902 AD in central China? (2) Were there any great temperature fluctuations during this period?

2. Data and methods

2.1 Phenological and temperature data

The Guanzhong Area (33°35'–35°50'N, 106°18'–110°37'E), located in central China (Figure 1), was selected as the study area because this area was where the capital city of the Sui and Tang dynasties (581–907 AD) was located. Many historical documents written by official historians or well-educated scholars who lived in the Guanzhong Area have been preserved. The study area has a continental monsoon climate with mean annual temperatures ranging from 7.8°C to 13.5°C and mean annual precipitation from 700 mm in the southwest to 500 mm in the northeast (Qian, 1991).

Eight historical documents were used to extract phenological data (Table 1). As historical phenological records were not strictly gathered according to modern, systematic guidelines, we identified the species and phenophases according to the semantics of description in the documents on the basis of phenological observation methods in China (Wan and Liu, 1979). For example, in 707 AD, Liu Xian, who was a government official, recorded the following information in his poem: “The flowers of peach are going to fall while the branches of willow are stretching”. From this poem, we extracted the end date of flowering for peach. Since peaches comprise many species, we defined it to a specific species according to the distribution range. As the distribution of *Amygdalus davidiana* was along the middle and lower reaches of the Yellow River (Gong, 1983) that matched our study area, we defined this particular phenological record as the end of flowering for *Amygdalus davidiana*. Other methods of species identification used in this study include the order of various phenophases known from modern observation and the history of plant introduction (Liu et al., 2014).

In addition, for phenophases such as the first/last date of snow and frost, the date was defined as the first/last appearance of these phenophases in each year. Some specific phenophases, for example, the beginning date of millet harvest, can be defined from the collection dates of grain tax in

Figure 1 Location of the Guanzhong Area, showing the modern names of cities mentioned in documentary records.

Table 1 Catalogue of historical documents used in this study^{a)}

Chinese name in Pinyin	Translated name in English	Author	Completion time	Time of records	Information to extract*
Sui Shu	The Book of Sui	Wei Zheng et al.	636 AD	581–618 AD	a ₁ , b, c
Jiu Tang Shu	Old Book of Tang	Liu Xu et al.	945 AD	618–907 AD	a ₁ , b, c
Xin Tang Shu	New Book of Tang	Song Qi et al.	1060 AD	618–907 AD	a ₁ , b, c
Zi Zhi Tong Jian	Comprehensive Mirror in Aid of Governance	Si Manguang et al.	959 AD	403 BC–959 AD	a ₁ , b, c
Ce Fu Yuan Gui	Prime Tortoise of the Record Bureau	Wang Qinruo et al.	1013 AD	2550 BC–907 AD	a ₁ , a ₂ , b
Quan Tang Shi	The Poetry of the Tang Dynasty	Peng Dingqiu et al.	1706 AD	618–907 AD	a ₁ , a ₂ , a ₃ , a ₄ , b, c
Tang Hui Yao	Institutional History of Tang	Wang Pu	961 AD	618–907 AD	a ₂
Tong Dian	General Institutions	Du You	801 AD	2550 BC–741 AD	a ₂

a) *information extracted: a: phenological information, including: a₁: seasonality of non-biological events; a₂: phenological information of agriculture; a₃: phenological information of ornamental plants; a₄: phenological information of animals; b: information on weather and climate related phenomena; c: information on human response to climate

autumn because the grain tax collection dates were directly connected to the timing of the grain harvest (Aono and Kazui, 2008; Aono and Saito, 2010; Kiss et al., 2011; Možný et al., 2012). Because the dates of historical events were recorded in the Chinese lunar calendar, all phenological dates were converted to the modern Gregorian calendar.

Using the abovementioned methods, we extracted a total of 271 records. These records can be classified into three categories (Table 1):

(1) Phenological records. There were a total of 87 phenological records over 77 years, including: (a) 42 phenophases on seasonality of non-biological events (first and last date of frost and snow), (b) 25 phenophases on agriculture (beginning date of spring cultivation, winter wheat harvest in summer and millet harvest in autumn), and (c) 20 phenophases on common ornamental plants (first flowering date of *Amygdalus davidiana* and *Paulownia fortune*, full-flowering date of *Amygdalus davidiana*, *Armeniaca vulgaris* and *Paeonia suffruticosa*, end flowering date of *Amygdalus davidiana* and beginning date of fruit drop of *Salix babylonica*). These phenological records were used to quantitatively reconstruct the temperature time series. The distribution of phenological records during the study period (600–

902 AD) is shown in Figure 2. On a 10-year scale, there was at least one phenological record in 83.9% of the periods. When it came to a 30-year scale, the percentage increased to 100%. Therefore, the phenological records extracted in this study were sufficient for reconstructing the temperature variation for the study period.

(2) Weather and climate related phenomena. The second category contained 168 records about weather and climate related phenomena such as snow, frost, second flowering of plants in winter and glaze ice.

(3) Human response. The third category contained 16 records of human responses describing the feeling of cold/warm events such as “extreme cold”, “be frozen to death” and “warm winter”.

The records of the second and third categories were used to verify the results of temperature reconstruction. For example, comparing the frequencies and duration of frost events in different periods can indirectly indicate a warm or cold climate.

Modern phenological data were derived from the China Phenological Observation Network (CPON) that is administered through the sponsorship of the Chinese Academy of Sciences. The phenological data in Xi'an, located in the

Figure 2 The number of phenological records extracted from historical documents every 10 years. Shaded bars indicate the number of phenological records. Blank bars represent the number of all historical records extracted.

center of Guanzhong Area, was selected to calibrate the phenology-temperature relationships. Xi'an has kept observations every year since 1963 except for the period of 1997–2002.

The corresponding temperature data of monthly mean temperature and daily temperature in Xi'an were obtained from the Chinese Meteorological Administration. Owing to a lack of data, some modern phenophases were defined based on the meteorological data. For instance, the modern dates of spring cultivation were defined using the criterion that daily mean temperature should be consecutively higher than 5°C for five days (Ge et al., 2010). The modern dating for harvesting millet in autumn is defined using the criterion that the daily mean temperature should be continuously lower than 10°C for five days (Hao et al., 2009).

2.2 Calibration and reconstruction

A growing number of studies have indicated that phenological events of plants are significantly related to temperature while other factors only play a secondary role (Sparks et al., 2000; Root et al., 2003; Badeck et al., 2004; Dai et al., 2013). Such correlations between temperature and phenophases establish the foundation for temperature reconstruction by phenological methods. As most of the historical phenological events used in our study occurred in different periods of a winter half-year, we reconstructed the WH temperature anomalies following the previous studies (Ge et al., 2003; Zheng et al., 2005; Ge et al., 2010). In addition, we calculated the correlation coefficients between modern phenological data and WH temperature/annual mean temperature respectively. All phenophases used in our study have fairly good correlations with WH temperatures for the corresponding year (Table 2). After fixing the time series of temperature and phenophases for anomalies with respect to the reference period (1961–1990), we developed transfer functions between the phenological and temperature anomalies by linear regression. The transfer functions can be expressed as:

pressed as:

$$y = ax_i + b, \quad (1)$$

where y is the annual WH temperature anomalies, and x_i is the phenological anomalies for phenophases. a and b are estimated using the least square method, and represent the regression slope and intercept, respectively. Uncertainties for the reconstruction were estimated by using the parameters a and b at the 95% confidence interval.

Subsequently, we applied phenophase-specific transfer functions to each historic phenological anomaly to obtain the temperature anomalies. If there was more than one record in a single year, temperature in that year was calculated as the arithmetic mean of all of the reconstructed temperatures in that year. The 10-year moving average was introduced to indicate the trend for temperature changes.

3. Results

Table 2 shows the transfer functions derived by fitting the linear regression between the phenological anomalies and the temperature anomalies of a corresponding year (with respect to the reference period 1961–1990). Most phenophases show a significant correlation with temperature on an interannual scale (Table 2), and 11 of 14 correlations are significant ($P < 0.05$). The standard error at a 95% confidence level is between 0.34 and 0.80°C, resulting in a mean reconstruction uncertainty of 0.63°C.

By using the abovementioned 87 data points of phenological records and corresponding transfer functions, we estimated the annual mean WH temperature for Guanzhong Area during 600–902 AD (Figure 3). As each year has two records over 10 years, mean temperatures for 77 years of the WH were reconstructed. In general, the mean temperature of the WH in Guanzhong Area during the study period was 0.23°C higher than at present. Temperatures mainly experienced two stages of change in the study period.

The first stage is between 600 and 800 AD, which was a relatively warm period. In this period, the mean temperature was 0.38°C higher than at present. This result was based on phenological evidence such as the advance in spring cultivation, first flowering of *Amygdalus davidiana*, beginning of winter wheat and millet harvest and delay in the first date of snow. For example, 13 of 15 records of spring cultivation showed earlier dates in this period. Other evidence from weather and climate related phenomena also supported our reconstruction. For instance, we found that 23 years had no snow in winter during the study period (600–902 AD), with 22 of those records (95.6%) in the period 600–800 AD. Human response evidence also indicated that it was relatively warm in this period. For example, *Zi Zhi Tong Jian* recorded “The emperor caught cold because of extreme high temperature in the capital in the 3rd lunar month in the 21st year of Zhen Guan Reign (April 10th to May 9th in 647 AD)”.

Table 2 Transfer functions for temperature reconstruction^{a)}

Phenophases	Transfer functions	Number of observations	Correlation coefficients	Standard error at 95% confidence level (°C)
First date of frost	$y=0.031x+0.044$	53	0.39**	±0.74
Last date of frost	$y=-0.030x-0.049$	53	-0.44**	±0.71
First date of snow	$y=0.0060x$	48	0.29	±0.34
Last date of snow	$y=-0.0030x$	46	-0.17	±0.35
Beginning date of spring cultivation	$y=-0.028x+0.19$	62	-0.38**	±0.77
Beginning date of winter wheat harvest	$y=-0.088x+0.89$	22	-0.56*	±0.60
Beginning date of millet harvest	$y=0.029x+0.30$	61	0.28*	±0.80
First flowering date of <i>Amygdalus davidiana</i>	$y=-0.067x+0.34$	38	-0.53**	±0.67
Full-flowering date of <i>Amygdalus davidiana</i>	$y=-0.075x+0.32$	38	-0.57**	±0.65
End flowering date of <i>Amygdalus davidiana</i>	$y=-0.058x+0.42$	37	-0.47**	±0.70
First flowering date of <i>Paulownia fortunei</i>	$y=-0.055x+0.60$	22	-0.54**	±0.70
Full-flowering date of <i>Paeonia suffruticosa</i>	$y=-0.074x+0.29$	38	-0.61**	±0.63
Full-flowering date of <i>Armeniaca vulgaris</i>	$y=-0.024x+0.15$	27	-0.28	±0.47
Beginning date of fruit drop of <i>Salix babylonica</i>	$y=-0.045x+0.43$	25	-0.69**	±0.62

a) *Correlated significantly ($P<0.05$; bilaterally), ** correlated significantly ($P<0.01$; bilaterally)

Figure 3 Reconstructed mean winter half-year temperature anomalies for Guanzhong Area based on phenological data in the period 600–902 AD (with respect to the mean climatology between 1961 and 1990). Dots represent annual mean temperature of winter half-year over 77 years. The black dotted line indicates temperature anomalies smoothed by the 10 year moving average. The gray area approximates the 95% confidence interval completed from linear regression error.

Someone died due to a severe heat wave in 736 AD according to *Jiu Tang Shu*. The highest WH temperature in this period was 1.75°C higher than that of the present (in the year 664 AD).

However, it was not consistently warmer during this period. Instead, cold events occurred occasionally. For example, the end of flowering for *Amygdalus davidiana* extracted from the abovementioned poem written by Liu Xian was delayed by 9 days, resulting in a 0.10°C lower average temperature than the present. Meanwhile, the temperature in 656 AD was very low (1.01°C lower than that of the present), based on the records that the first frost of the year was at least 34 days earlier than that of the present. Cold events were also reflected in human responses. *Xin Tang Shu*, *Jiu Tang Shu* and *Ce Fu Yuan Gui* recorded 3 data points of

people or animals frozen to death respectively in this period.

The temperature declined suddenly around the 800s. The mean WH temperature of 800–902 AD was 0.08°C lower than that of 1961–1990. This result was based on phenological evidence such as the delay in full-flowering dates of *Paeonia suffruticosa* and *Armeniaca vulgaris* and the advance in the first date of snow. For example, *Xin Tang Shu* and *Jiu Tang Shu* both recorded that on the 10th day of the 8th lunar month (September 20th) of 820 AD, it snowed in Guanzhong Area, indicating that the first date of snow was advanced by 56 days, resulting in a 0.34°C lower temperature than the present. For evidence of weather- and climate-related phenomena, there were 86 instances of cold events (frost and snow) in our study period, suggesting the mean frequency of cold events was 0.28 during 600–902 AD. Nevertheless, the frequency of cold events was 0.39 in the period 800–902 AD. In particular, heavy snow appeared 34 times in historical documents, while no snow in winter was recorded only 4 times during this period. Human responses also revealed that it was colder in this period. Han Yu, a famous poet in the Tang dynasty, recorded in his poem “Bitter Cold”: “Even getting close to the stove, I cannot feel warm” in 803 AD. Ten years later, he wrote another poem, documenting that: “The snow lay several feet thick in the capital. It is colder than a normal year”.

4. Discussion

Documentary data notably differ from classical natural archives, and long established uncertainty criteria (e.g., sampling and calibration uncertainty) are complemented or replaced by other information (Pfister et al., 2008). Reconstruction uncertainties in our study are addressed as follows. The first category of uncertainties is from the historical

documents themselves. The Chinese historical documents have the characteristic of only recording the extreme events rather than the ordinary conditions. This pattern has been observed by many Chinese researchers (Ge and Zhang, 1990; Zheng et al., 2005; Hao et al., 2009). Therefore, in our study, the temperature constructed from the evidence of snow and frost events may reflect extreme climatic conditions, causing unmanageable uncertainties. The second category of uncertainties results from transfer functions. As Table 2 shows, the transfer from phenophases to temperature can cause uncertainties of 0.34–0.80°C. However, in most cases, this type of uncertainty did not impact the relative cool or warm pattern, but only affected the magnitude of warming or cooling (Figure 3).

To assess the validity of our temperature reconstruction for 600–902 AD in Guanzhong Area, we compared our results with other relative studies of temperature reconstructions. For the purpose of an effective comparison, we first converted annual temperature anomalies into 30-year mean temperature anomalies (Figure 4a). Then, we compared the results with two previous studies. The first was WH temperature anomalies at a 30-year resolution reconstructed from documentary evidence in the middle and lower reaches of the Yellow and Yangtze Rivers compared with 1951–1980 (Ge et al., 2003) (Figure 4b). The second was annual temperature anomalies reconstructed from tree rings in Asia relative to the reference period of 1961–1990 (Ahmed et al., 2013) (Figure 4c). The reconstruction by Ge et al. (2003) found that the WH temperature was 0.29°C higher than the present, which is similar to our reconstruction (0.23°C higher). Furthermore, both reconstructions by Ge et al. (2003) and our study indicated that a clear shift from warm to cold occurred around the 800s and the coldest years were focused on the last decades of the period. The amplitude of

Ge et al. (2003) was 1.70°C, which was very similar to our result (1.33°C). Other than contrast of our reconstructions to that of the document-based ones, we compared our reconstruction to a tree-ring-based series reflecting the temperature variations in Asia (Figure 4c). The cold period of approximately 800–900 AD in our reconstruction was confirmed by the other two series. And the similar temperature fluctuations among these three studies confirm the effectiveness of using historical documents, especially the phenological records, to reconstruct past climate change. In addition, we gathered more evidence than the previous studies, improving the reliability of the reconstruction results.

However, differences exist among these temperature time series. The results of Ge et al. (2003) decreased nonlinearly from the beginning to the end of the study period, while the time series from our reconstruction experienced warm-cold-warm-cold fluctuations. Furthermore, the degrees of warmth/coldness varied between the two reconstructions. The warmest 30-year period of our reconstruction was 600–630 AD with a temperature that was 0.86°C higher than the present, while the coldest 30-year period was 870–900 AD with a temperature that was 0.24°C lower than the present. For Ge et al. (2003), the maximum and minimum WH temperature anomaly was, respectively, +1.10°C from 630–660 AD and –0.60°C from 870–900 AD. The differences between Ahmed et al. (2013) and our study focused on the degrees of coldness during the period of 800–900 AD. The discrepancies among these three reconstructions can be ascribed to the proxy data themselves, the evidence utilized, the study areas and the temporal resolutions because the three studies used different proxy data, covered different geographical regions and were synthesized to different temporal resolutions (annual or 30 years).

5. Conclusions

Although many studies have documented climate change in the Sui and Tang Dynasties, this is the first time systematic phenological records were applied to analyze the climatic conditions in the Tang Dynasties. In the course of the analysis, we extracted phenological records from historical documents as a proxy and calibrated transfer functions between temperature and phenophases. As a result, the WH temperatures in Guanzhong, China, for the period 600–902 AD were constructed. The results showed that the mean temperatures in the Guanzhong Area during the study period were generally warmer than those of the reference period (1961–1990). The first 200 years in the study period were warmer, with a mean temperature that was 0.38°C higher than the reference period, but the temperature became 0.08°C lower than the present during the period of 800–902 AD. These conclusions provide a valuable contribution to understanding climatic variability during the Sui and Tang dynasties in China. This study provides the foundation for

Figure 4 Comparison of reconstructed temperature anomalies for 600–900 AD. (a) The winter half-year temperature reconstruction of our study with 30-year temporal resolution in Guanzhong Area in this study; (b) the winter half-year temperature reconstruction of the middle and lower reaches of the Yellow and Yangtze Rivers with a 30-year temporal resolution by documents (Ge et al., 2003); (c) the annual mean temperature reconstruction of whole Asia with 30-year temporal resolution by tree rings (Ahmed et al., 2013). The black dotted line indicates the original series of annual mean temperature.

further studies on phenological conditions in the Sui and Tang Dynasty, as well as the relationship of ecosystem response to climate changes in the study period.

Acknowledgements *This research was supported by the Key Project of the National Natural Science Foundation of China (Grant No. 41171043), the National Basic Research Program of China (Grant No. 2012CB955304) and the National Natural Science Foundation of China (Grant No. 41430528).*

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