



Could phenological records from Chinese poems of the Tang and Song dynasties (618–1279 CE) be reliable evidence of past climate changes?

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Abstract. Phenological records in historical documents have been proven to be of unique value for reconstructing past climate changes. As a literary genre, poetry reached its peak in the Tang and Song dynasties (618–1279 CE) in China. Sources from this period could provide abundant phenological records in the absence of phenological observations. However, the reliability of phenological records from poems, as well as their processing methods, remains to be comprehensively summarized and discussed. In this paper, after introducing the certainties and uncertainties of phenological information in poems, the key processing steps and methods for deriving phenological records from poems and using them in past climate change studies are discussed: (1) two principles, namely the principle of conservatism and the principle of personal experience, should be followed to reduce uncertainties; (2) the phenological records in poems need to be filtered according to the types of poems, background information, rhetorical devices, spatial representations, and human influence; (3) animals and plants are identified at the species level according to their modern distributions and the sequences of different phenophases; (4) phenophases in poems are identified on the basis of modern observation criteria; (5) the dates and sites for the phenophases in poems are confirmed from background information and related studies. As a case study, 86 phenological records from poems of the Tang Dynasty in the Guanzhong region in China were extracted to reconstruct annual temperature anomalies in spe-

cific years in the period between 600 and 900 CE. Following this, the reconstruction from poems was compared with relevant reconstructions in published studies to demonstrate the validity and reliability of phenological records from poems in studies of past climate changes. This paper reveals that the phenological records from poems could be useful evidence of past climate changes after being scientifically processed. This could provide an important reference for future studies in this domain, in both principle and methodology, pursuant of extracting and applying phenological records from poems for larger areas and different periods in Chinese history.

1 Introduction

Phenology is the study of recurring biological life cycle stages and the seasonality of non-biological events triggered by environmental changes (Schwartz, 2003; Richardson et al., 2013). Phenological data derived from historical documents have been widely used as proxies to reflect past climatic changes around the world, especially in Europe and Asia. The records of grape harvest dates (Chuine et al., 2004; Meier et al., 2007; Maurer et al., 2009; Daux et al., 2012; Možný et al., 2016; Labbé et al., 2019), grain harvest dates (Nordli, 2001; Kiss et al., 2011; Wetter and Pfister, 2011; Možný et al., 2012; Pribyl et al., 2012; Brázdil et al., 2018), and ice break-up dates (Tarand and Nordli, 2001; Nordli et al., 2007; Etien et al., 2008) have been adopted to re-

construct past climate changes in Europe. In Japan, cherry blossom records have been used to reconstruct spring temperatures dating back to the medieval period (800–1400 CE) (Aono and Kazui, 2008; Aono and Saito, 2010; Aono, 2015).

In China, occasional phenological observations began around 2000 years ago, and they have been recorded in various documents. These documents can be further divided into sources produced by institutions and sources generated by individuals. The former includes Chinese classical documents and local gazettes, as well as the archives of the Qing Dynasty (1644–1911 CE) and the Republic of China (1912–1949 CE) (Ge et al., 2008). Based on the documents produced by institutions, abundant phenological records have been extracted to reconstruct past climate changes in specific regions and periods in China (Chu, 1973; Ge et al., 2003; Zheng et al., 2005; Hao et al., 2009; Liu et al., 2016; Fei, 2019). However, the phenophases recorded in these documents are mainly non-organic, such as “ice phenology” (the time of freezing and opening of water-bodies), “snow phenology” (the dates of first and last snowfall), and “frost phenology” (the dates of first and last frosts). The limited amount of organic phenophases that do occur in these documents are principally “agricultural phenology” (e.g., the commencement dates of spring cultivation, winter wheat harvest in summer, and millet harvest in autumn). Therefore, it is difficult to compare the phenological data from documents produced by institutions with those from modern observations, which largely focus on the seasonal changes of natural plants. In contrast, the phenological information in personal documents (mostly private diaries) is much more varied and includes records about both non-organic and organic events, such as flowers blossoming, leaf expansion and discoloration, and fruit ripening (Ge et al., 2008; Liu et al., 2014; Zheng et al., 2014). Using phenological evidence from diaries, many studies have reconstructed past climate changes in different regions and periods in China (Fang et al., 2005; Xiao et al., 2008; Ge et al., 2014; Wang et al., 2015; Zheng et al., 2018). However, the diaries were most abundant within the past 800 years, especially in the Ming Dynasty (1368–1644 CE), the Qing Dynasty, and the Republic of China. The earliest diary found in China so far (The Diary of Genzi-Xinchou by Lv Zuqian) only dates back to 1180 CE (Ge et al., 2018). Thus, there is a lack of phenological records on natural plants and animals before the 1180s.

China enjoyed unprecedented economic prosperity, political stability, and a relatively open society in the Tang and Song dynasties (618–1279 CE). The Imperial Examination System, a civil service examination system in imperial China for selecting candidates for the state bureaucracy, had gradually improved, and poetry was incorporated into the examination subjects during this period (Zhang, 2015). In these contexts, as a literary genre, poetry reached its peak during the Tang and Song dynasties in ancient China. A very diverse array of people in the Tang and Song dynasties, from emperors to civilians, preferred to record their thoughts and daily

lives in poems. Abundant phenological information that was provided in poems of the Tang and Song dynasties is a valuable source for phenological records in this period.

Although many studies have indicated that there was a Medieval Warm Period (MWP) in China consistent with many other parts of the world, disputes still exist regarding the start and end time, regional differences, and the extent of warming in different periods of the MWP in China (Zhang et al., 2003; Yang et al., 2007; Ge et al., 2013). The period of the Tang and Song dynasties coincided with the MWP in China. More reconstruction studies of the Tang and Song dynasties based on high-resolution proxies will contribute to a better understanding of these controversial issues. Extracting phenological records from poems of the Tang and Song dynasties is an effective way to improve the resolution of proxy data in this period. However, it is an extraordinary challenge to extract phenological records from poems due to the use of rhetorical devices, the limitations of poetic rules and forms, and the conventions of rhymes and sounds in the poems. In addition, the phenological evidence in poems does not always follow modern criteria, which could lead to considerable uncertainties if the real phenophases in poems were not properly identified.

Chu (1973) laid the foundation for climate reconstructions based on documents and has been highly praised worldwide for his efforts. Although a few subsequent studies (Man, 1998; Ge et al., 2010) adopted phenological evidence from poems to reconstruct climate changes, further systematic and specialized research on deriving phenological records from poems of the Tang and Song dynasties still needs to be carried out.

In this study, we first introduce the characteristics of phenological information in poems, including its accessibility and inherent uncertainties. We then put forward basic principles and key processing steps for extracting phenological records from poems of the Tang and Song dynasties. We also compare phenological records from poems with other proxies in the reconstruction of past climate changes in the Guanzhong region of central China as a case study. Our overall objectives are to demonstrate the validity and reliability of phenological records from poems as a proxy of past climate changes and to provide a reference, both theoretical and methodological, for the extraction and application of phenological records from poems.

2 The certainties and uncertainties of phenological information in poems from the Tang and Song dynasties

As a special carrier of historical phenological information, poetry has both certainties and uncertainties vis-à-vis applications to past climate changes. For example, in the study by Chu (1973), which laid the foundation for climate reconstructions based on documents, 17 pieces of evidence were

from poems and 11 of them were phenological information of the Tang and Song dynasties. Most of the phenological information from poems used by Chu (1973) was valid and the reconstructed results have been verified by other studies, which demonstrates the certainties of phenological records from poetry. However, other phenological evidence such as the orange trees in the Guanzhong region used by Chu (1973) may be less certain. For instance, some studies have pointed out that the orange trees in the Guanzhong region recorded in the poems of the Tang Dynasty (618–907 CE) were transplanted from other places and were taken care of by specialized personnel in the Imperial Palace (Man, 1990; Mu, 1996). Therefore, the certainties and uncertainties of phenological information in poems from the Tang and Song dynasties need to be analyzed before being used in studies of past climate changes.

2.1 The certainties of phenological information from poems

Poetry is one of the major genres of Chinese literature. It expresses peoples' social lives and spiritual worlds with concise and emotive words according to the requirements of certain syllables, tones, and rhythms. The poetry of the Tang and Song dynasties represents the highest level of poetry development and has become a treasure of Chinese traditional literature. People in the Tang and Song dynasties exhibited a preference for recording and sharing their lives and ideas via poems, which is akin to recording in diaries in the later dynasties. Phenology, which could be used to indicate seasons and guide agricultural activities, is one of the favorite topics of poets. As most of the poems were improvised, they commonly reflect the real-time experiences of the poets. In addition, the great mass of the poems passed down to contemporary times were written by well-educated scholars, who were able to describe the phenological phenomena they saw without misusing or abusing words. Thus, poetry is an excellent carrier of phenological information.

Regarding the different types of poems of the Tang and Song dynasties, phenological information is most abundant in natural poems and realistic poems. The natural poems describe the force and beauty of nature, such as mountains, rivers, animals, and plants; they contain almost all kinds of phenological records, spanning both organic and non-organic sources (Table 1). The realistic poems strive for typicality in images, authenticity in details, and objectivity in descriptions. For example, there is a line in a poem by Bai Juyi that is as follows: “there is a crescent moon on the third night and the cicada sings for the first time” (Supplement S1-1), which specifically records the phenology of the first call of cicadas. Generally speaking, the phenological information from poems, especially natural poems and realistic poems, is objective and authentic and can thus be leveraged as a data source for reconstructing past climatic changes.

2.2 The quantity, spatial distribution, and accessibility of phenological records from the poems

By their very nature, Chinese poems have many distinctions in terms of recording phenological information compared to documents produced by institutions and personal diaries (Table 2). Poems have evident advantages in the quantity and variety of phenological evidence. According to *Quan-Tang-Shi* (the poetry of the Tang Dynasty) (Peng et al., 1986) and *Quan-Song-Shi* (the poetry of the Song Dynasty) (Center for Ancient Classics and Archives of Peking University, 1999), nearly 50 000 poems from the Tang Dynasty and more than 270 000 poems from the Song Dynasty are preserved. Numerous phenological records in the poems include not only non-organic events but also a variety of organic phenomena, most of which concern the phenology of natural plants and animals.

The spatial distributions of the phenological records are highly consistent with the ruling regions of the dynasties and there is a positive relationship between the quantity of records preserved from particular areas and the level of development of those areas. Take the Song Dynasty (960–1279 CE) as an example: because northern China was dominated by the Jin Dynasty from 1127 to 1279 CE, the phenological records from *Quan-Song-Shi* of this period are mainly located in southern China, especially around the city of Hangzhou (the capital city of the Song Dynasty at that time).

In general, the accessibility of phenological records in poems tends to be lower than that of other documents. Unlike documents produced by institutions in which phenological evidence was recorded by dedicated individuals, the phenological evidence in poems was recorded more inadvertently. The information about phenophases in poems may be incomplete or ambiguous. For a specific phenophase, a poet usually only recorded it a few times in poems during his lifetime. Thus, the frequency and continuity of the phenophase in his poems were relatively low. Take the word “willow” as an example: it was mentioned in 9041 poems in the *Quan-Tang-Shi* and the *Quan-Song-Shi*, but clear species names, phenophases, dates, and sites can be obtained from only 80 (0.88 %) poems. The accessibility of phenological records in poems may vary depending on particular characteristics of the poets. For example, Li Bai and Du Fu are the most representative romantic poet and realistic poet in the Tang Dynasty, respectively. According to *Quan-Tang-Shi*, there were 896 poems written by Li Bai and 1158 poems written by Du Fu. Among them, 23 (2.56 %) poems by Li Bai and 76 (6.56 %) poems by Du Fu are related to phenology. Thus, the accessibility of phenological information from poems by Du Fu is more than twice that of Li Bai. Only by integrating the same phenophase recorded by different poets could improvements be made in terms of frequency and continuity.

Table 1. Different types of phenology in poems from the Tang and Song dynasties.

Types of phenology		Example quotes from poems
Non-organic	phenology of ice	All the springs are frozen and stagnant (Supplement S1-2).
	phenology of snow	It snows in the eighth lunar month in frontier regions (Supplement S1-3).
	phenology of frost	Frost falls in the eighth lunar month of every year (Supplement S1-4).
Organic	phenology of agriculture	The people have just finished planting mulberry trees to raise silkworms, and they are going to transplant rice seedling again (Supplement S1-5).
	phenology of natural plants	Ume blossoms begin to bloom in early winter (Supplement S1-6).
	phenology of animals	The river reflects the autumn scenery and the geese begin to fly south (Supplement S1-7).

Table 2. Comparisons among the phenological evidence from poems, diaries, and documents produced by institutions in China.

	Poems	Diaries	Documents produced by institutions
Types of phenological evidence	organic (phenology of plants and animals) and non-organic (phenology of ice, snow, and frost)	organic (phenology of plants and animals) and non-organic (phenology of ice, snow, and frost)	mostly non-organic (phenology of ice, snow, and frost) and a few organic (agricultural phenology)
Amount of phenological evidence	more	more	less
Reasons for phenological record-keeping	memory of daily life/expressing feelings	memory of daily life/observing phenology	recording extreme climatic events and agriculture-related activities
Frequency of phenological record-keeping	sporadic	sporadic to phenophase-specific recurrent	phenophase-specific recurrent
Continuity of phenological record-keeping	intermittent	intermittent/less than the lifetime of the observer	up to the occurrence of extreme climatic events
Species clarity	ambiguous to species-specific	ambiguous to species-specific	most clear
Phenophases clarity	ambiguous to phenophase-specific	ambiguous to phenophase-specific	most clear
Spatial clarity	ambiguous to inferable	clear/inferable	most clear
Temporal clarity	ambiguous to inferable	clear/inferable	most clear

2.3 The inherent uncertainties of phenological evidence in poems

In addition to the uncertainties arising from data interpretation, calibration, validation, and verification, the extraction of phenological evidence from poems could also be associated with inherent uncertainties during the identification of species, the identification of phenophases, and the ascertainment of dates and sites. Such uncertainties need to be identified as a precursor to using phenological records to reconstruct past climate changes.

2.3.1 Uncertainties in the identification of species

Because the Chinese language has not changed fundamentally during the long history of the country, the people in present-day China can read ancient poems without too much difficulty. Nevertheless, some changes in meanings and expressions of particular words and phrases still exist. Partic-

ular words or phrases may have several additional meanings in ancient Chinese in comparison to modern usage. For example, the phrase “jin hua” (mainly refers to golden flower in modern Chinese) has at least four meanings in the Quan-Tang-Shi, but only one of them is a substantial description of phenology (Table 3).

The different names of some specific species in ancient China have also been simplified and unified in contemporary language. For example, the si sheng du juan (*Cuculus micropterus*) had at least three different names during the Tang and Song dynasties (Table 4). It is also noteworthy that the names of plants and animals in poems were mostly recorded at the genera level due to the lack of modern taxonomic knowledge. Nevertheless, different species within the same genus may exhibit divergent responses to climate change according to modern phenological studies (Dai et al., 2013). Thus, large uncertainties exist during the identification of species in poems.

Table 3. Different meanings of the Chinese phrase “jin hua” in poems of the Tang Dynasty.

Pinyin of the verse	Meanings of “jin hua” in the poems
fan ci huang jin hua (Supplement S1-8)	chrysanthemum (inferred from context)
sheng li jin hua qiao nai han (Supplement S1-9)	decorations on ladies’ headwear
xuan miao mei jin hua (Supplement S1-10)	an alchemistic term for Taoist priests
cui wei jin hua bu ci ru (Supplement S1-11)	golden patterns on the tails of peacocks

Table 4. Comparisons among the ancient, modern, and Latin names of several common species.

Species	Pinyin of ancient name	Pinyin of modern names	Latin name
Animals	si jiu, zi gui, du yu	si sheng du juan	<i>Cuculus micropterus</i>
	cang geng, shang geng, chu que, huang niao	hei zhen huang li	<i>Oriolus chinensis</i>
	xuan niao, yi niao, luan niao, tian nv, wu yi	jia yan	<i>Hirundo rustica</i>
	tiao, fu yu, ni, qi nv	cao chan	<i>Mogannia conica</i>
Plants	fu qu, fu rong, han dan	lian	<i>Nelumbo nucifera</i>
	lu, wei, jian jia	lu wei	<i>Phragmites australis</i>
	shan shi liu, ying shan hong, shan zhi zhu	du juan	<i>Rhododendron simsii</i>
	mu li, ming zha, man zha	mu gua	<i>Chaenomeles sinensis</i>

2.3.2 Uncertainties in the judgment of phenophases

Phenophases in poems are not recorded in strict accordance with modern systematic criteria but are described through multiple rhetorical devices such as metaphor, personification, hyperbole, quote, pun, and rhyme. As such, it is difficult to extract clear phenophases from poems. For example, there is a line in a poem by the poet Quan Deyu as follows: “peonies occupy the spring breeze with their fragrance alone” (Supplement S1-12), which describes the phase of peonies flowering. However, the phenophase in this line is equivocal due to the use of personification. To compare the phenological records from poems with corresponding modern observational phenophases, the exact phenological stages need to be identified from the first flowering date, the full-flowering date, and the end of flowering date. Therefore, uncertainties may be produced during the identification of specific phenophases.

2.3.3 Uncertainties in ascertainment of dates

Exact dates are crucial for quantitatively evaluating phenological and climatic changes from past to present. By converting the Chinese lunar calendar into the modern Gregorian calendar, the phenophases in the poems can be compared with modern observational phenophases. Some poems may contain precise temporal information. For example, the poet Bai Juyi recorded the following in his poem: “the azalea is falling and the cuckoo is singing in this year” (Supplement S1-13). The title of this poem is “Farewell spring (written on the 30th day of the third month of the 11th year of the Yuan He)” – Yuan He is one of the reign titles of the Tang Dynasty, and the corresponding Gregorian date of this poem

is 30 April 816 CE. However, the time of writing was not explicitly recorded for most other poems. Any lack of information concerning year, month, or day may lead to failures in phenological and climatic reconstructions. For instance, in another poem by Bai Juyi he states “people are busy in the fifth lunar month because the wheat is yellow in the field” (Supplement S1-14). Here, only information concerning the month was directly presented in this poem, which could obviously lead to uncertainties when deducing the year and the day. To make matters worse, some poems were written according to the memories or imaginations of poets. The information from such poems thus needs to be excluded.

2.3.4 Uncertainties in ascertainment of sites

By matching the ancient name of a site with its modern name, the phenophases in poems can be compared with the corresponding observational phenophases at the same site. However, similar to dates, the sites of phenophases in poems are sometimes missing. Worse still, some names of sites mentioned in poems are imagined for the purpose of expressing emotions rather than to record real locations. For example, Lu You wrote a verse in his poem which reads “there are so many willow branches in Ba Qiao, but who would have thought of sending one to me” (Supplement S1-15). Ba Qiao is a location in Xi’an (a city in central China), which is more than 700 km away from the place where Lu You wrote this poem (Chengdu, China). By describing the willow branches in his hometown in this poem, the poet expressed his homesickness. When attempting to ascertain sites, these kinds of uncertainties should be carefully considered and dealt with appropriately.

3 The methods of processing phenological records in poems from the Tang and Song dynasties for past climate studies

To minimize the uncertainty during the extraction of clear species, phenophases, dates, and sites from poems and to render them comparable with modern observations, several fundamental principles and processing steps should be put forward.

3.1 The basic principles for data processing

3.1.1 The principle of conservatism

The principle of conservatism refers to deducing ambiguous information conservatively in order to keep the characteristics of phenological information without causing too much deviation. Take the aforementioned poem of Bai Juyi (Supplement S1-14) as an example: the poem was written in 807 CE in Xi'an according to background information, while the exact date is not recorded. From the poem, we know that the harvest date of wheat in that year appeared in the fifth lunar month (from 10 June to 8 July in the Gregorian calendar), and thus 10 June, which is the closest to the modern observations (from 26 May to 8 June with the average of 2 June), can be determined as the date of wheat harvest in 807 CE in Xi'an. It should be noted that if the recorded period in the poem overlaps with the time of the modern phenophase, the principle of conservatism is inapplicable, and the record in the poem is invalid.

3.1.2 The principle of personal experience

The principle of personal experience demands that the phenological information described in the poems was being experienced by the poet, thus excluding records based on imaginations or memories. For example, Yang Wanli recorded a line in his poem which stated that “begonias in my hometown are flowering on this date and I see them blooming in my dream” (Supplement S1-16). From this, we know that he was not in his hometown when he wrote this poem. Thus, the phenophase of Begonias in this poem cannot be used. It is more complex to diagnose the information in some poems. For example, Lu You wrote a poem in 1208 CE wherein the following is recorded: “the Begonias in Biji Fang (place name) are the best in the world. Each branch looks dyed with scarlet blood” (Supplement S1-17). By looking into the life experience of Lu You, this poem is found to record his memory of 1172 CE. Therefore, this poem cannot be used as phenological evidence either according to the principle of personal experience.

3.2 The key steps of data processing

On the basis of the foregoing principles, four steps are required for the processing of phenological records in poems (Fig. 1).

3.2.1 Step 1: filtering the records

1. *Filtering the records according to the features of poets and poems.*

Poems commonly reflect the thoughts and daily lives of the poets. Thus, the poems written by people in certain professions that have little contact with phenological events, such as the alchemists mentioned in Table 3, may contain little phenological information. In this way, the poems written by alchemists can be excluded to improve the accessibility of phenological evidence from the poems. Furthermore, the records can be filtered according to the styles of poems and the interests or life experiences of the poets. For example, it is more likely that phenological records can be extracted from pastoral poems than from history-intoned poems.

2. *Filtering the records according to the background information.*

According to the background information of a poem, we can judge whether the phenophases in the poem actually happened, thus ensuring the robustness of phenological evidence. For example, there is a line in a poem by Su Shi as follows: “a few branches of peach blossom outside the bamboo grove, and the ducks will notice the warming of the river firstly” (Supplement S1-18). This seems to describe the natural phenophases in spring. However, by looking into the background information, we know that this poem refers to a painting. Therefore, it describes the scenery within the painting instead of real nature. The record thus needs to be excluded.

3. *Filtering the records according to the rhetorical devices.*

Whether the use of rhetorical devices in poems affects the authenticity of phenophases needs to be distinguished. For instance, despite the rhetorical device of personification used in the aforementioned poem by Quan Deyu (Supplement S1-12), it does reflect the blossom of peonies. Thus, this poem can be used in the study of past climate changes. The line of Lu Zhaoling saying that “the water in Laizhou (place name) has become shallower several times and how ripe is the peach fruit” (Supplement S1-19) seems to enquire about the time of the peach phenophase, but it is actually referring to the myth that peaches mature once every 3000 years in wonderland. The rhetorical device of quotation in this line has affected the authenticity of phenophases. Thus, this record should be eliminated.

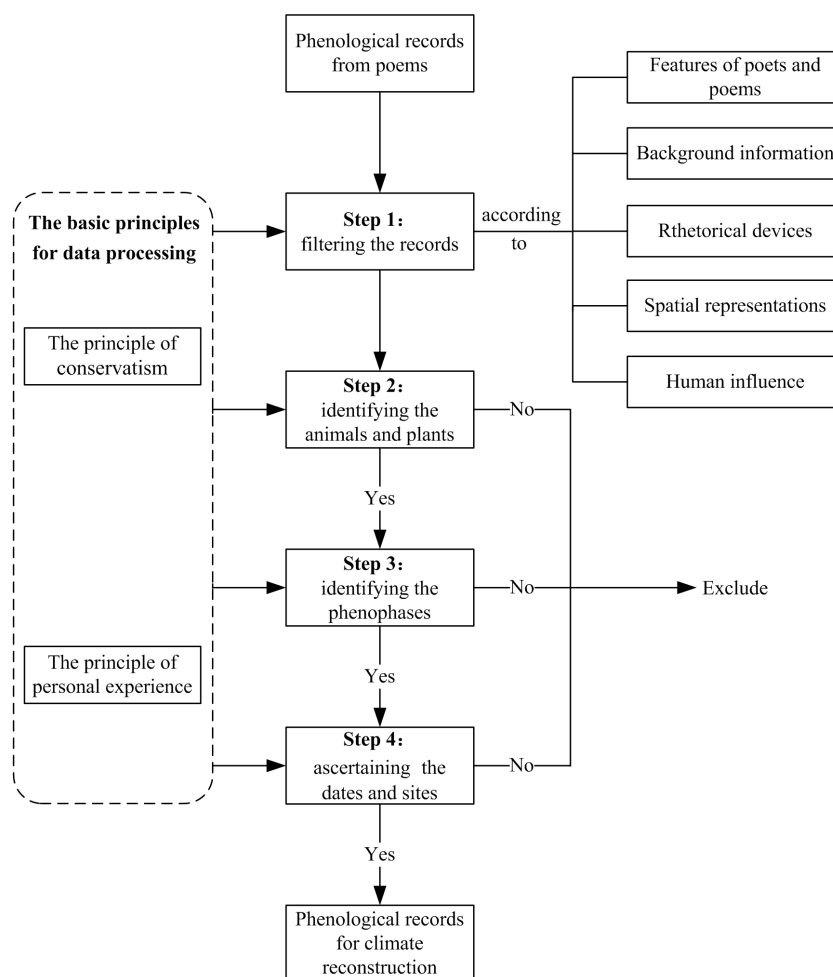


Figure 1. Processing steps of phenological records in poems for climate reconstructions.

4. Filtering the records according to the spatial representations.

For a specific species, phenophases vary with latitude, longitude, and elevation. It is necessary to clarify the spatial representation of phenological records in poems and to select records that are not affected by the local microclimate. For example, Bai Juyi recorded in his poem that “all the flowers on the plain have withered in the fourth lunar month, but the peaches in the temple on the mountain just begin to bloom” (Supplement S1-20). This record cannot be directly compared with modern observational data because the difference in altitude is almost 1000 m between the mountain in the poem and the modern observation site on the plain. Other factors that contribute to spatial differences such as valleys, depressions, and heat island effects are also used to filter the records.

5. Filtering the records according to human influence.

Human activities, such as cultivation and transplantation, could also affect the phenophases of plants. To accurately reflect climate changes, it is necessary to filter the records that were affected by human activities. Take the orange trees in the imperial palace of the Tang Dynasty as an example. Some researchers pointed out that these oranges were transplanted from southern China and could not normally survive the winter on the Guanzhong Plain. Thus, they were intensively managed by humans. This kind of phenological information in poems cannot be used as an indicator of climate changes.

3.2.2 Step 2: identifying animals and plants at the species level

There are two principal ways of identifying the animals and plants in poems from the genera level to the species level. The first way involves identifying the species according to the modern distribution of different species under the genera. For instance, the poet Liu Xian recorded the following information in his poem: “the flowers of peaches are going to fall while the branches of willow are stretching” (Supplement S1-21). This poem was written in Xi’an, which is located in the middle reaches of the Yellow River. Historically, the main peach species were *Amygdalus davidiana* and *Amygdalus persica*. According to modern species distributions, the former species can be found along the middle and lower reaches of the Yellow River, while the latter occurs in the Huai River basin (Gong et al., 1983). Thus, the peach in the poem can be identified as *A. davidiana*. The second way is to identify the species according to the sequences and correlations of different phenophases. For example, Gao Shi wrote a poem in Chengdu wherein it is stated that “the green-up of willow leaves and the ume blossoms can’t stop me from being sad” (Supplement S1-22). The ume plant in ancient Chinese language usually refers to *Chimonanthus praecox* or *Armeniaca mume*. From the content of the text, we can infer that the ume blossoms occurred at a similar time to the leaf expansion of willow. According to modern observation data in Chengdu, the average full leaf expansion date of willow (*Salix babylonica*) is 23 February, while the average full-flowering dates of *Chimonanthus praecox* and *Armeniaca mume* are 10 January and 10 February, respectively. The average date of full flowering for *A. mume* is closer in time with the average date of full leaf expansion for willow. Thus, the ume blossoms in the poem can be identified as *A. mume*.

3.2.3 Step 3: identifying the phenophases according to modern observation criteria

By applying the semantic differential technique, which is commonly used in the studies of past climate changes (Academy of Meteorological Science of China Central Meteorological Administration, 1981; Wang, 1991; Wei et al., 2015; Yin et al., 2016; Su et al., 2018; Fang et al., 2019), the descriptions in poems are classified and graded according to the criteria of the phenological observation methods in China (Wan and Liu, 1979; Gong et al., 1983; Fang et al., 2005). Taking the aforementioned poem of Quan Deyu (Supplement S1-12) as an example, a line describes a scene where many peonies were blooming and filling the spring breeze with strong perfume. By classifying and grading the key words “occupy” and “fragrance” in this poem with other common descriptions of flowering phases in poems such as “tender”, “sparse”, “flourish”, “dense”, “wither”, and “fallen”, the description of peony blooming in this poem was most likely to match with the full-flowering date under

the modern criterion “more than half of the flowers have blossomed in the observed species”. Thus, the phenophase in the poem can be identified as the full-flowering date. The classification and grading results for some representative examples of phenological descriptions in poems are shown in Table 5.

3.2.4 Step 4: ascertaining the dates and locations

This step firstly sought temporal information, including clear year, month, and date of the phenophase, from the titles, prefaces, and lines of the poems. The missing time information could then be deduced by consulting the background information and related studies or estimated reasonably according to the principle of conservatism. Finally, the time information in the Chinese lunar calendar had to be converted into the modern Gregorian calendar. For example, the poet Cui Riyong recorded in his poem that “the ume blossoms in the palace smell fragrant and look delicate with the background of snow” (Supplement S1-29). The title of this poem indicates that this poem records a banquet in the imperial palace on People’s Day (Chinese traditional festival on the seventh day of the first lunar month). From the poem, we do not know which year it was. However, this banquet was also recorded by Xin Tang Shu (New Books of Tang, a history book of the Tang Dynasty) in the year 730 CE. Hence, we know that this poem was written in 730 CE.

Similarly, the exact location of the sites could be confirmed. It should be checked whether the place names appearing in the poems are real sites for phenophases. For example, Ba Qiao is not the site of the phenophase for willow in the aforementioned poem by Lu You (Supplement S1-15). Thus, the record in this poem cannot be used as phenological evidence for past climate studies.

4 Validation of the phenological records from poems for reconstructing past climate changes: a case study of temperature reconstruction in the Guanzhong region for specific years during 600–900 CE

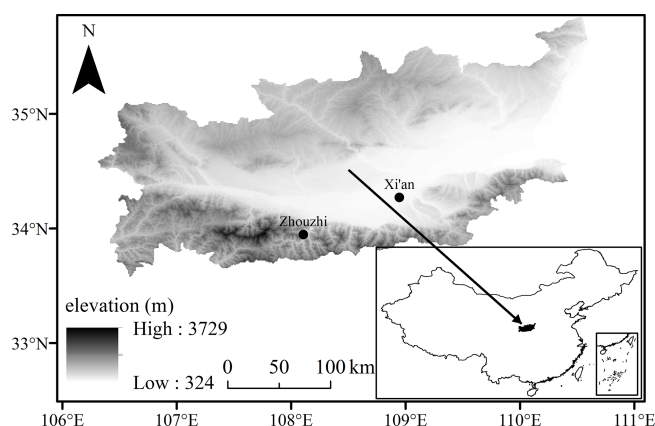
To test the reliability of phenological records in poems for past climate change studies and the validity of the processing methods outlined in this study, we extracted 86 phenological records (Appendix A) from poems of the Tang Dynasty to reconstruct the mean annual temperatures in the Guanzhong region of China during the period of 600–900 CE.

4.1 Study area

The Guanzhong region (33°35′–35°50′ N, 106°18′–110°37′ E), located in central China (Fig. 2), was where the capital city of the Tang dynasty was located. Many poets were active here and left many poems describing phenology during the Tang dynasty. The study area has a continental monsoon climate with mean annual temperatures ranging

Table 5. Classification and grading results for representative examples of phenological descriptions in poems.

Phenophase	Translation of the original verses	Description in the modern observation criteria
First song	New cicada tweeted two or three times (Supplement S1-23)	The date of first call
First appearance	New swallow came ten days before the festival of She (Supplement S1-24)	The date of first appearance
First leaf	Willow leaves are tender just as a beauty frowns slightly (Supplement S1-25)	The date when the first one or two leaves are spread out
Full leaf expansion	The green lotus leaves stretch to the horizon (Supplement S1-26)	The date when the leaflets on half of the branches of the observed tree are completely flat
First flowering	The hibiscus is at the beginning of the red and it covers the palace (Supplement S1-27)	The date when the petals of one or several flowers begin to open fully
Full flowering	Peonies occupy the spring breeze with their fragrance alone (Supplement S1-12)	The date when more than half of the flowers have blossomed in the observed species
End of flowering	The flowers of peach are going to fall while the branches of willow are stretching (Supplement S1-21)	The date when there are very few flowers on the observed trees
Fruit drop	The willows and poplars in the street are shrouded in smog (Supplement S1-28)	The date when <i>Salix</i> spp. and <i>Populus</i> spp. begin to have fluffy catkins

**Figure 2.** The location of the Guanzhong region for the climatic reconstructions in this study with the modern names of sites mentioned in the poems. Publisher's note: please note that the above figure contains disputed territories.

from 7.8 to 13.5 °C and mean annual precipitation from 500 mm in the northeast to 700 mm in the southwest (Qian, 1991).

4.2 Data and methods

Since the 86 records from poems pertain to diverse phenophases, they indicate temperature changes at different times of the year. To obtain a relatively uniform and comparable series of reconstructed temperatures, the mean annual temperature anomaly was selected as the reconstruction index. Transfer functions between annual temperature anomalies and corresponding phenophases were established by using modern observation data. The transfer functions were then applied to reconstruct the annual temperature anomaly

lies (with the reference period of 1961–1990 CE) in the Guanzhong region during 600–900 CE. The modern phenological and meteorological data used and the detailed methods of the transfer functions are shown in Appendix B.

4.3 Results and comparisons with other reconstructions

Figure 3a shows the reconstructed annual temperature anomalies using the phenological records from poems. For validation purposes, the results were compared with relevant studies. The first series used for comparison is attributable to Liu et al. (2016), wherein winter half-year (from October to next April) temperature anomalies were reconstructed by 87 phenological records from historical documents (mostly produced by institutions) for the period 600–902 CE in the Guanzhong region. The reconstruction by Liu et al. (2016) is a reliable reference not only because of the study area and period considered coincide but also because the proxies used by that study and ours are phenological records from independent sources. To avoid the additional influences of reconstruction indicators and transfer functions, the records from Liu et al. (2016) were reconstructed to annual temperature anomalies (Fig. 3b).

Table 6 shows the historical data sources, types, and quantity of phenological evidence in Liu et al. (2016) and this study. Except for a single record in one poem (Appendix A, poem No. 13), there is no duplication in records between the two studies. In general, the two studies are based on similar quantities of evidence, while the data types used in the two studies are quite different. In terms of Liu et al. (2016), 71 of 87 (nearly 82 %) pieces of phenological data are from documents produced by institutions. Among the 87 pieces of evidence, 67 (more than 77 %) are non-organic phenophases or agricultural phenophases (Fig. 3b). By contrast, the vast majority (more than 96 %) of evidence from poems in this study

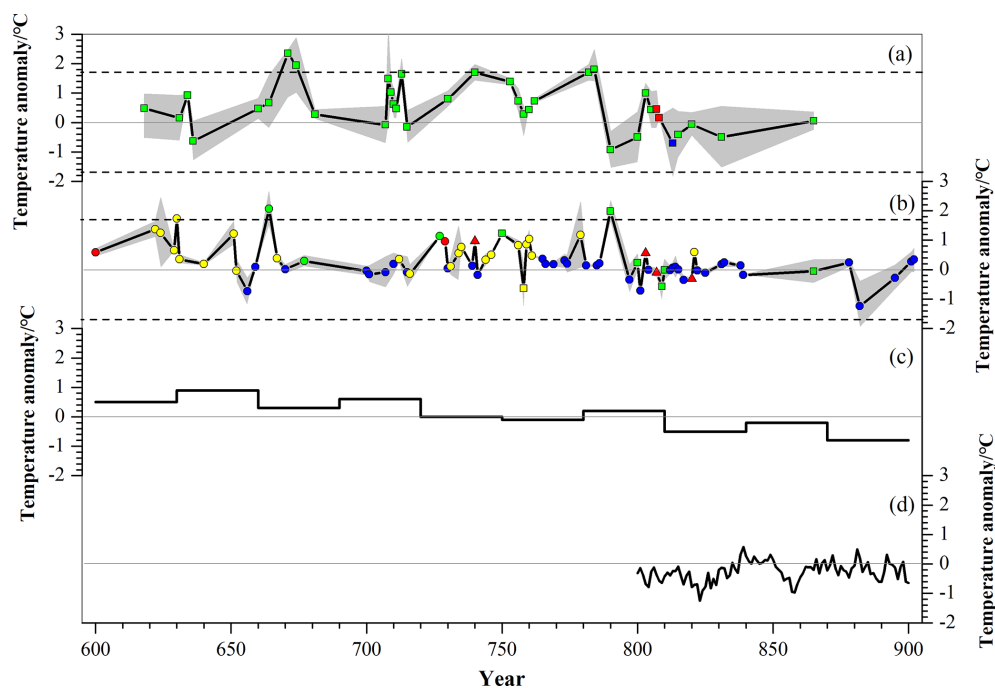


Figure 3. Comparison of reconstructed temperature anomalies for 600–900 CE (with respect to the mean climatology between 1961 and 1990): **(a)** annual mean temperature anomalies reconstructed by phenological records from poems in this study; **(b)** annual mean temperature anomalies reconstructed using the phenological records from historical documents by Liu et al. (2016); **(c)** winter half-year temperature anomalies reconstructed from historical documents for the middle and lower reaches of the Yellow and Yangtze Rivers with a 30-year temporal resolution by Ge et al. (2003); and **(d)** annual mean temperature reconstructed from tree rings for the whole of Asia by Ahmed et al. (2013). Squares denote temperature anomalies reconstructed from poems, circles denote temperature anomalies reconstructed from documents of institutions, triangles denote temperature anomalies reconstructed from both poems and documents of institutions, green denotes temperature anomalies reconstructed by phenophases of wild plants, yellow denotes temperature anomalies reconstructed by agricultural phenophases, blue denotes temperature anomalies reconstructed by non-organic phenophases, red denotes temperature anomalies reconstructed by at least two types of phenophases, the gray area approximates the 95 % confidence interval according to ordinary least-squares (OLS) regression, and the dotted lines indicate the 2 standard deviation range of 1.72 °C of the modern period (1951–2013).

Table 6. Comparisons of data sources, types, and numbers of records used in Liu et al. (2016) and in this study.

	Liu et al. (2016)			This study
	Documents of institutions	Poems	Total	Poems
Non-organic phenophases	42	0	42	1
Agricultural phenophases	24	1	25	1
Phenophases of natural plants	5	15	20	83
Phenophases of animals	0	0	0	1
Total	71	16	87	86

are phenophases of wild plants (Fig. 3a). These differences suggest that the phenological records in poems are effective supplements to historical phenological evidence for the period of the Tang Dynasty. It is also worth noting that fewer years are reconstructed in this study (36) compared to in Liu et al. (2016) (76), which further supports the claim that the frequency and continuity of phenological records preserved in poems is more sporadic than that of documents produced by institutions (Table 2).

To assess the validity of the temperature reconstruction from poems, two more temperature reconstructions by different proxies were leveraged for comparison. The first was winter half-year temperature anomalies at a 30-year resolution reconstructed from documentary evidence in the middle and lower reaches of the Yellow and Yangtze Rivers of China (Ge et al., 2003) (Fig. 3c). The second was annual temperature anomalies reconstructed from tree rings in Asia (Ahmed et al., 2013) (Fig. 3d). All four reconstructions indicated that

there were more relatively cold years in the later periods after around the 800s. Indeed, the coldest years according to all four reconstructions occurred in this period. Before the 800s, the reconstructions by Liu et al. (2016), Ge et al. (2003), and our study showed more relatively warm temperatures, with the warmest years occurring around the 660s. Furthermore, the amplitude of reconstructed temperature by Liu et al. (2016) was 3.30 °C, which was very similar to the amplitude of reconstructed temperature (3.28 °C) in our study. As a benchmark, according to modern data spanning 1951–2013 the amplitude was 3.97 °C. In sum, the similarities between different reconstructions confirm the effectiveness of phenological records from poems for gauging past climate changes.

5 Discussion

There are still controversies about how the climate changed during the Tang and Song dynasties (Chu, 1973; Fei et al., 2001; Yang et al., 2002; Ge et al., 2003; Tan et al., 2003; Thompson et al., 2006; Zhang and Lu, 2007). One of the reasons lies in the lack of sufficient evidence supporting the climatic reconstructions. Although some studies have reconstructed the temperatures during this period using natural evidence such as tree rings, pollen, and sediment (Xu et al., 2004; Zhang et al., 2014; Zhu et al., 2019), their results either do not cover the entire period or they have relatively low temporal resolution. In addition, these natural proxies are mostly collected from uninhabited areas, and thus they are not particularly amenable to evaluating the interactions between climate change and human activities. In comparison, documentary evidence, which occurs more frequently and is closer to human life, has become an important data source for reconstructing climate changes in this period. As one of the most popular literary forms in the Tang and Song dynasties, poetry has huge potential to provide abundant and diverse phenological information, which will undoubtedly contribute to the study of historical climate change.

Despite this, very few studies have thus far been reported concerning the use of phenological records from poems to quantitatively reconstruct historical climate change due to the lack of effective methodologies for data extraction. Unlike climate reconstructions using other proxies that have standard processing methods and clear reference objects, the processing of phenological records from poems is much more complex. For example, dating tree-ring samples only requires counting the number of annual rings from the outside to the inside or comparing them with a standard chronology. However, the temporal information in poems cannot be obtained directly from a reference chronology. As already mentioned, the temporal information in poems may be hidden in the poet's biography, official history books, or some related studies. It is necessary to search through these materials one by one and make careful comparisons before ascertaining

the exact temporal information, and indeed some information is found to be unrecorded after searching through large amounts of material. This problem also exists when seeking to extract information concerning species, phenophases, and sites from poems.

We attempt to introduce a standard procedure for extracting phenological records from poems, which could, on the one hand, minimize the uncertainties of the records, and on the other hand, efficiently filter irrelevant records. By following the principles and steps herein, researchers can understand where to find the information needed and how to manage the phenological data from poems. The extracted phenological records are comparable with modern observation data and can be used as a proxy for quantitatively reconstructing climate changes.

Although the validity of phenological records from poems has only been tested in a single area of China in the Tang Dynasty, the methodologies of extracting and processing phenological records from poems for climate reconstructions proposed in this study could be applied to wider regions and longer periods. On the one hand, many studies have demonstrated that climate is the primary driver of phenophases over the whole of China (Piao et al., 2006; Dai et al., 2014; Ge et al., 2015; Tao et al., 2017), which indicates that the phenological records obtained at any place could be used as evidence of climate changes. On the other hand, historians agree that the feudal society in Chinese history did not fundamentally change during different dynasties (Liu, 1981; Tian, 1982; Feng, 1994). Although historical China varied its administrated area coverage from dynasty to dynasty, its core socioeconomics closely aligned with the major agricultural areas throughout history. This geographic and temporal overlap allows for continuous comparison across the core areas of China (Fang et al., 2019). Correspondingly, the essence of literature, especially poetry, has not changed, though different types of poetry varied in their popularity between dynasties, e.g., differences in terms of poetic forms, the number of words, and the needs of rhymes and sounds. Therefore, the phenological records obtained from poems from different periods in core areas of historical China can also be extracted and processed for climatic reconstruction according to the method in this study.

We only used 86 phenological records extracted from poems to reconstruct the temperature anomalies for a small area in the Tang Dynasty. Although the uncertainties from transfer functions are shown in Appendix C, there are other uncertainties that are difficult to quantitatively assess. For example, differences in cultivated plant types and crop management may have an effect on the temperature reconstruction, though many studies show that phenological changes in cultivated plants are principally driven by climate changes, especially temperature variations (Estrella et al., 2007; Lobell et al., 2012; Liu et al., 2018). Overall, the reconstruction in this study testifies to the reliability of phenological records from poems in indicating past climate changes. Nevertheless,

there are still many phenological records that remain to be extracted. By rough estimation, the temporal resolution of the phenological records from poems of the Tang and Song dynasties can reach 20 years or less. In addition, phenological records from poems of the Tang and Song dynasties are widely distributed, covering almost all the regions of modern China. Take the Song Dynasty (960–1279 CE) as an example. Although northern China was dominated by the Jin Dynasty from 1127 to 1279 CE, which means that most poems written by poets living in northern China are not contained in the *Quan-Song-Shi*, we can try to search from the *Quan-Jin-Shi* (the Poetry of the Jin Dynasty) (Xue and Guo, 1995) to add phenological records in northern China. The rich records around the capitals and developed cities are of great value in terms of comparisons with modern phenological observations. Future work will be focused on extracting more records from poems and developing integration methods for different phenophases at different sites to explore the overall phenological changes and climate changes over a larger region.

6 Conclusions

In this study, we put forward a processing method to extract phenological information from poems of the Tang and Song dynasties, which includes two principles (the principle of conservatism and the principle of personal experience) and four steps: (1) filtering the records based on the features of poets and poems, the background information, the rhetorical devices, the spatial representations, and human influence; (2) identifying the animals and plants to the species level; (3) judging the phenophases according to modern observation criteria; and (4) ascertaining times and sites. We then used this method to extract 86 phenological records from poems of the Guanzhong region in central China and reconstructed the annual mean temperature anomalies for specific years during 600–900 CE. The reconstructed temperature anomaly series was comparable with that reconstructed by records from documents in the same area and period, demonstrating that our method is effective and reliable. This paper therefore provides a reference in both theory and method for the extraction and application of phenological records from poems in studies of past climate changes.

Appendix A

Table A1. Phenological records from poems used in the reconstruction of this study.

No.	Gregorian date	Site	Phenophase	Translation of the original verses
1	28 Jun 618	Xi'an	End flowering date of <i>Punica granatum</i>	It missed the spring because of late blooming (Supplement S1-30).
2	27 Feb 631	Xi'an	Full leaf expansion date of <i>Salix babylonica</i>	The leaves of willow welcome the third lunar month and the ume blossoms take the two years apart (Supplement S1-31).
3	27 Feb 631	Xi'an	Full-flowering date of <i>Armeniaca mume</i>	The leaves of willow welcome the third lunar month and the ume blossoms take the two years apart (Supplement S1-31).
4	18 Jan 634	Xi'an	Full-flowering date of <i>Chimonanthus praecox</i>	There are no leaves on the willow tree, but flowers on the ume tree (Supplement S1-32).
5	27 Apr 636	Xi'an	Full-flowering date of <i>Juglans regia</i>	Peach flowers blossom for those who are going away (Supplement S1-33).
6	10 Sep 660	Xi'an	Full-flowering date of <i>Osmanthus fragrans</i>	Only Osmanthus blooms near the south hill (Supplement S1-34).
7	31 Aug 664	Xi'an	End flowering date of <i>Osmanthus fragrans</i>	Osmanthus is at the end of flowering in the moonlight and the ume tree is at the beginning of flowering under the beam (Supplement S1-35).
8	31 Aug 664	Xi'an	First flowering date of <i>Chimonanthus praecox</i>	Osmanthus is at the end of flowering in the moonlight and the ume tree is at the beginning of flowering under the beam (Supplement S1-35).
9	8 Feb 671	Xi'an	First flowering date of <i>Armeniaca mume</i>	Ume blossoms early in the palace and the willow is new near the creek (Supplement S1-36).
10	8 Feb 671	Xi'an	First leaf date of <i>Salix babylonica</i>	Ume blossoms early in the palace and the willow is new near the creek (Supplement S1-36).
11	18 Feb 674	Xi'an	Full leaf expansion date of <i>Salix babylonica</i>	The wicker swings to show its beauty (Supplement S1-37).
12	11 Aug 681	Xi'an	Fruit maturity date of <i>Amygdalus davidiana</i>	The peaches in the palace are very luxuriant (Supplement S1-38).
13	6 Apr 707	Xi'an	End flowering date of <i>Amygdalus davidiana</i>	The flowers of peach are going to fall while the branches of willow are stretching (Supplement S1-21).
14	6 Apr 707	Xi'an	Full leaf expansion date of <i>Salix babylonica</i>	The flowers of peaches are going to fall while the branches of willow are stretching (Supplement S1-21).
15	4 Feb 708	Xi'an	First leaf date of <i>Salix babylonica</i>	The delicate wicker on the embankment has not turned yellow (Supplement S1-39).
16	4 Feb 708	Xi'an	First flowering date of <i>Armeniaca mume</i>	The fragrance of ume blossoms and the color of willows can withstand praise (Supplement S1-40).
17	4 Feb 708	Xi'an	First leaf date of <i>Salix babylonica</i>	The fragrance of ume blossoms and the color of willows can withstand praise (Supplement S1-40).
18	4 Feb 708	Xi'an	First flowering date of <i>Armeniaca mume</i>	The fragrance of ume blossoms seems to be obscured by beautiful singing (Supplement S1-41).
19	4 Feb 708	Xi'an	First flowering date of <i>Armeniaca mume</i>	Ume blossoms vie to bloom in the palace (Supplement S1-42).
20	4 Feb 708	Xi'an	First flowering date of <i>Armeniaca mume</i>	The ume blossoms and willows in the palace can recognize the weather (Supplement S1-43).
21	4 Feb 708	Xi'an	First leaf date of <i>Salix babylonica</i>	The ume blossoms and willows in the palace can recognize the weather (Supplement S1-43).
22	4 Feb 708	Xi'an	First flowering date of <i>Amygdalus davidiana</i>	Why do peaches and plums compete to bloom (Supplement S1-44).
23	4 Feb 708	Xi'an	First flowering date of <i>Prunus salicina</i>	Why do peaches and plums compete to bloom (Supplement S1-44).

Table A1. Continued.

No.	Gregorian date	Site	Phenophase	Translation of the original verses
24	4 Feb 708	Xi'an	First flowering date of <i>Armeniaca vulgaris</i>	New apricot blossoms adorn the palace and ume blossoms bloom at the feast (Supplement S1-45).
25	4 Feb 708	Xi'an	First flowering date of <i>Armeniaca mume</i>	New apricot blossoms adorn the palace and ume blossoms bloom at the feast (Supplement S1-45).
26	10 Feb 709	Xi'an	Full-flowering date of <i>Chimonanthus praecox</i>	The flicking of snow on the branches adds to the beauty of ume blossoms (Supplement S1-46).
27	21 Feb 709	Xi'an	First flowering date of <i>Armeniaca mume</i>	Ume blossoms and willow catkins are new (Supplement S1-47).
28	15 Mar 709	Xi'an	Full leaf expansion date of <i>Salix babylonica</i>	The willows leaves are all open over the city (Supplement S1-48).
29	15 Mar 709	Xi'an	Full leaf expansion date of <i>Salix babylonica</i>	Willows secretly urge the late spring (Supplement S1-49).
30	17 Apr 709	Xi'an	Beginning date of fruit drop of <i>Salix babylonica</i>	The willow by the river flicks the emperor's goblet (Supplement S1-50).
31	16 Oct 709	Xi'an	End flowering date of <i>Osmanthus fragrans</i>	The Osmanthus fell into the goblet full of wine (Supplement S1-51).
32	4 Mar 710	Xi'an	Full-flowering date of <i>Armeniaca mume</i>	The ume blossoms remain white when the cold is over while the willows have not turned yellow when the wind is late (Supplement S1-52).
33	4 Mar 710	Xi'an	Full leaf expansion date of <i>Salix babylonica</i>	The ume blossoms remain white when the cold is over while the willows have not turned yellow when the wind is late (Supplement S1-52).
34	4 Mar 710	Xi'an	Full leaf expansion date of <i>Salix babylonica</i>	There are thousands of willows unfolding their leaves (Supplement S1-53).
35	25 Mar 710	Guanzhong	Full-flowering date of <i>Amygdalus davidiana</i>	There are red flowers all over the ground and the whole banquet is filled with fragrance (Supplement S1-54).
36	25 Mar 710	Guanzhong	Full-flowering date of <i>Amygdalus davidiana</i>	The red calyxes bloom against the dawn in the garden (Supplement S1-55).
37	25 Mar 710	Guanzhong	Full-flowering date of <i>Amygdalus davidiana</i>	The peach blossoms are bright and seem to have brilliance (Supplement S1-56).
38	25 Mar 710	Guanzhong	Full-flowering date of <i>Amygdalus davidiana</i>	Countless flowers bloom among the flowers by the water (Supplement S1-57).
39	25 Mar 710	Guanzhong	Full-flowering date of <i>Amygdalus davidiana</i>	The gorgeous flowers in the garden accompany the beauty (Supplement S1-58).
40	3 Apr 710	Guanzhong	End flowering date of <i>Amygdalus davidiana</i>	The peach blossoms by the Wei River fall into the water (Supplement S1-59).
41	4 Apr 710	Xi'an	Full-flowering date of <i>Amygdalus davidiana</i>	When the peaches and plums bloom in spring, the scenery of the capital city is good (Supplement S1-60).
42	4 Apr 710	Xi'an	Full-flowering date of <i>Prunus salicina</i>	When the peaches and plums bloom in spring, the scenery of the capital city is good (Supplement S1-60).
43	4 Apr 710	Xi'an	Beginning date of fruit drop of <i>Salix babylonica</i>	The red calyx exudes fragrance and the branches of willows are surrounded by green ribbons (Supplement S1-61).
44	4 Apr 710	Xi'an	Full-flowering date of <i>Amygdalus davidiana</i>	The red calyx exudes fragrance and the branches of willows are surrounded by green ribbons (Supplement S1-61).
45	5 Apr 710	Xi'an	End flowering date of <i>Armeniaca mume</i>	The ume blossoms in the palace glowed against the snow and the willow trees in the city were full of smog (Supplement S1-62).
46	5 Apr 710	Xi'an	Beginning date of fruit drop of <i>Salix babylonica</i>	The ume blossoms in the palace glowed against the snow and the willow trees in the city were full of smog (Supplement S1-62).

Table A1. Continued.

No.	Gregorian date	Site	Phenophase	Translation of the original verses
47	5 Apr 710	Xi'an	Beginning date of fruit drop of <i>Salix babylonica</i>	The willows and ume blossoms in the palace are covered with green ribbons (Supplement S1-63).
48	5 Apr 710	Xi'an	End flowering date of <i>Armeniaca mume</i>	The willows and ume blossoms in the palace are covered with green ribbons (Supplement S1-63).
49	5 Apr 710	Xi'an	Beginning date of fruit drop of <i>Salix babylonica</i>	The willows are covered with green smog (Supplement S1-64).
50	6 Apr 710	Xi'an	Beginning date of fruit drop of <i>Salix babylonica</i>	The green ribbons from the willows float at the banquet (Supplement S1-65).
51	6 Apr 710	Xi'an	End flowering date of <i>Amygdalus davidiana</i>	Red peach blossoms and emerald green willows adorn the fete (Supplement S1-66).
52	6 Apr 710	Xi'an	Beginning date of fruit drop of <i>Salix babylonica</i>	Red peach blossoms and emerald green willows adorn the fete (Supplement S1-66).
53	9 May 710	Xi'an	First flowering date of <i>Hibiscus syriacus</i>	Trees cover the palace and the hibiscuses start to turn red (Supplement S1-67).
54	24 Mar 711	Guanzhong	Full-flowering date of <i>Prunus salicina</i>	The peach and plum blossoms are lost in their own fragrance (Supplement S1-68).
55	24 Mar 711	Guanzhong	Full-flowering date of <i>Amygdalus davidiana</i>	The peach and plum blossoms are lost in their own fragrance (Supplement S1-68).
56	14 Feb 713	Xi'an	End flowering date of <i>Chimonanthus praecox</i>	The garden is only accompanied by withered ume blossoms in spring (Supplement S1-69).
57	28 Feb 713	Xi'an	First leaf date of <i>Salix babylonica</i>	The branches of willows are fresh (Supplement S1-70).
58	7 Apr 715	Xi'an	End flowering date of <i>Amygdalus davidiana</i>	The pool water is covered with peach blossoms (Supplement S1-71).
59	29 Jan 730	Xi'an	Full-flowering date of <i>Chimonanthus praecox</i>	The ume blossoms in the palace smell fragrant and look delicate with the background of snow (Supplement S1-29).
60	3 Apr 740	Xi'an	Beginning date of fruit drop of <i>Salix babylonica</i>	People at the banquet all resent the falling catkins (Supplement S1-72).
61	10 Apr 753	Xi'an	Beginning date of fruit drop of <i>Salix babylonica</i>	The catkins fall like snowflakes (Supplement S1-73).
62	5 Feb 756	Xi'an	Full-flowering date of <i>Chimonanthus praecox</i>	The umes bloom towards the sky (Supplement S1-74).
63	18 Mar 758	Xi'an	First leaf date of <i>Salix babylonica</i>	There are thousands of tender branches of willows in the palace (Supplement S1-75).
64	18 Mar 758	Xi'an	Full-flowering date of <i>Amygdalus davidiana</i>	Peach blossoms are as red as drunk (Supplement S1-76).
65	15 Apr 758	Xi'an	End flowering date of <i>Amygdalus davidiana</i>	The peach blossoms wither after the catkins (Supplement S1-77).
66	15 Apr 758	Xi'an	Beginning date of fruit drop of <i>Salix babylonica</i>	The peach blossoms wither after the catkins (Supplement S1-77).
67	3 Apr 760	Xi'an	Full-flowering date of <i>Pyrus betulaefolia</i>	Pear flowers bloom during the Cold Food Festival (Supplement S1-78).
68	18 Mar 762	Xi'an	Full leaf expansion date of <i>Salix babylonica</i>	Flowers and willows in every village bloom of their own accord (Supplement S1-79).
69	3 Apr 782	Xi'an	Beginning date of fruit drop of <i>Salix babylonica</i>	In spring the city is full of flying catkins (Supplement S1-80).
70	25 Feb 784	Xi'an	First leaf date of <i>Salix babylonica</i>	The flowers and willows in the capital are fresh (Supplement S1-81).
71	19 Apr 790	Xi'an	Full-flowering date of <i>Paeonia suffruticosa</i>	Peonies occupy the spring breeze with their fragrance alone (Supplement S1-12).
72	4 Apr 800	Xi'an	Beginning date of fruit drop of <i>Salix babylonica</i>	The sycamore blooms after the willow catkins (Supplement S1-82).
73	4 Apr 800	Xi'an	First flowering date of <i>Firmiana platanifolia</i>	The sycamore blooms after the willow catkins (Supplement S1-82).

Table A1. Continued.

No.	Gregorian date	Site	Phenophase	Translation of the original verses
74	4 Apr 800	Xi'an	First flowering date of <i>Amygdalus davidiana</i>	Peach and plum flowers are fresh in every courtyard (Supplement S1-83).
75	4 Apr 800	Xi'an	First flowering date of <i>Prunus salicina</i>	Peach and plum flowers are fresh in every courtyard (Supplement S1-83).
76	4 Apr 800	Xi'an	First flowering date of <i>Paulownia fortunei</i>	Paulownia blooms on Qingming Festival (Supplement S1-84).
77	2 May 805	Xi'an	End flowering date of <i>Paulownia fortunei</i>	The purple paulownia flowers are falling and the birds are singing (Supplement S1-85).
78	7 Aug 805	Xi'an	First sing date of <i>Cryptotympana atrata</i>	A new cicada calls two or three times (Supplement S1-86).
79	1 May 807	Zhouzhi	End flowering date of <i>Paeonia suffruticosa</i>	When I come back, the peony flowers are all over (Supplement S1-87).
80	10 Jun 807	Zhouzhi	Beginning date of winter wheat harvest	People are busy in the fifth lunar month because the wheat is yellow in the field (Supplement S1-14).
81	22 Oct 808	Xi'an	First date of frost	Frost falls in the ninth lunar month and it turns cold early in autumn (Supplement S1-88).
82	27 Sep 813	Xi'an	Full-flowering date of <i>Osmanthus fragrans</i>	Osmanthus by the railing exudes fragrance (Supplement S1-89).
83	13 May 815	Xi'an	Beginning date of fruit drop of <i>Salix babylonica</i>	Willow catkins are flying all over the sky just like snowflakes (Supplement S1-90).
84	3 Apr 820	Xi'an	Full-flowering date of <i>Armeniaca vulgaris</i>	Although the apricot blossoms here are better than in other places, I still want to see the flowers in my hometown (Supplement S1-91).
85	24 Sep 831	Xi'an	Full-flowering date of <i>Osmanthus fragrans</i>	The cold dew wet the Osmanthus quietly (Supplement S1-92).
86	4 Apr 865	Xi'an	End flowering date of <i>Armeniaca vulgaris</i>	Apricot flowers seem to be sad with me together (Supplement S1-93).

Appendix B: The modern data sources and reconstructing method in this study

Modern phenological observation data in Xi'an, which located in the center of Guanzhong region, were derived from the China Phenological Observation Network (CPON). Xi'an has kept observations every year since 1963, except for the period of 1997–2002. The annual mean temperature data of 1951–2013 in Xi'an was 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 date of spring cultivation was defined as the first day when the daily mean temperature is consecutively higher than 5 °C for 5 d (Ge et al., 2010). The modern date of millet harvest in autumn is defined as the first day when the daily mean temperature is continuously lower than 10 °C for 5 d (Hao et al., 2009).

After changing the time series of temperature and phenophases to anomalies with respect to the reference period (1961–1990 CE), the transfer functions between the phenological and temperature anomalies were developed by linear regression, which can be expressed as

$$y = ax_i + b, \quad (\text{B1})$$

where y is the annual temperature anomalies and x_i is the phenological anomalies for phenophase i . The constants a and b are estimated using the least-squares method and represent the regression slope and intercept, respectively.

Subsequently, the phenophase-specific transfer functions were applied to each historic phenological anomaly to obtain the annual 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.

Appendix C

Table C1. Transfer functions for the temperature reconstructions based on phenological records obtained from Liu et al. (2016) and from poems in this study.

Phenophases	Transfer functions	Number of observations	Correlation coefficients	Standard error at 95 % confidence level (°C)
First date of frost	$y = 0.033x + 0.423$	53	0.432 ^b	0.742
Last date of frost	$y = -0.033x + 0.386$	53	-0.475 ^b	0.724
First date of snow	$y = 0.010x - 0.023$	26	0.467 ^a	0.321
Last date of snow	$y = -0.006x - 0.019$	26	-0.335	0.336
First sing date of <i>Cryptotympana atrata</i>	$y = 0.013x + 0.012$	15	0.638	0.216
Beginning date of spring cultivation	$y = -0.030x + 0.232$	62	-0.396 ^b	0.792
Beginning date of winter wheat harvest	$y = -0.084x + 1.284$	22	-0.570 ^b	0.584
Beginning date of millet harvest	$y = 0.024x + 0.336$	61	0.231	0.806
First flowering date of <i>Amygdalus davidiana</i>	$y = -0.075x + 0.361$	38	-0.573 ^b	0.667
Full-flowering date of <i>Amygdalus davidiana</i>	$y = -0.086x + 0.331$	38	-0.634 ^b	0.630
End flowering date of <i>Amygdalus davidiana</i>	$y = -0.069x + 0.441$	37	-0.531 ^b	0.691
Fruit maturity date of <i>Amygdalus davidiana</i>	$y = 0.022x + 0.740$	13	0.495	0.505
First flowering date of <i>Armeniaca mume</i>	$y = -0.044x + 0.626$	14	-0.436	0.785
Full-flowering date of <i>Armeniaca mume</i>	$y = -0.055x + 0.590$	14	-0.507	0.752
End flowering date of <i>Armeniaca mume</i>	$y = -0.061x + 0.586$	14	-0.617 ^a	0.717
First flowering date of <i>Armeniaca vulgaris</i>	$y = -0.029x + 0.119$	24	-0.320	0.467
Full-flowering date of <i>Armeniaca vulgaris</i>	$y = -0.045x + 0.196$	20	-0.517 ^a	0.402
End flowering date of <i>Armeniaca vulgaris</i>	$y = -0.028x + 0.135$	24	-0.331	0.466
First flowering date of <i>Chimonanthus praecox</i>	$y = -0.007x + 0.669$	26	0.196	0.845
Full-flowering date of <i>Chimonanthus praecox</i>	$y = -0.011x + 0.770$	25	-0.218	0.813
First flowering date of <i>Firmiana platanifolia</i>	$y = -0.016x + 0.135$	14	-0.217	0.486
First flowering date of <i>Hibiscus syriacus</i>	$y = -0.014x + 0.060$	18	-0.457	0.456
Full-flowering date of <i>Juglans regia</i>	$y = -0.076x + 0.441$	33	-0.663 ^a	0.612
Full-flowering date of <i>Osmanthus fragrans</i>	$y = -0.069x + 0.306$	17	-0.611 ^b	0.716
End flowering date of <i>Osmanthus fragrans</i>	$y = 0.044x + 0.486$	22	0.497 ^a	0.728
Full-flowering date of <i>Paeonia suffruticosa</i>	$y = -0.088x + 0.307$	38	-0.703 ^b	0.581
End flowering date of <i>Paeonia suffruticosa</i>	$y = -0.065x + 0.493$	36	-0.446 ^b	0.731
First flowering date of <i>Paulownia fortunei</i>	$y = -0.062x + 0.688$	22	-0.607 ^a	0.813
End flowering date of <i>Paulownia fortunei</i>	$y = -0.055x + 1.103$	18	-0.382	0.901
First flowering date of <i>Prunus salicina</i>	$y = -0.068x + 0.585$	13	-0.740 ^b	0.515
Full-flowering date of <i>Prunus salicina</i>	$y = -0.068x + 0.591$	13	-0.779 ^b	0.480
End flowering date of <i>Punica granatum</i>	$y = 0.056x + 0.257$	21	-0.450	0.825
Full-flowering date of <i>Pyrus betulaefolia</i>	$y = -0.076x + 0.441$	27	-0.698 ^b	0.608
First leaf date of <i>Salix babylonica</i>	$y = -0.052x + 0.745$	31	-0.471 ^b	0.711
Full leaf expansion date of <i>Salix babylonica</i>	$y = -0.042x + 0.511$	37	-0.384 ^a	0.753
Beginning date of fruit drop of <i>Salix babylonica</i>	$y = -0.091x + 1.312$	17	-0.707 ^b	0.602

^a $P < 0.05$, ^b $P < 0.01$

Note that the original verses and sources of the poems in Chinese used in this paper can be found in the Supplement.

Data availability. All the data used to perform the analysis in this study are described and properly referenced in the paper. The phenological records from poems used to reconstruct the annual temperatures are listed in Appendix A, and all of the original sources of the verses used in this paper are listed in the Supplement in Chinese. The modern phenological data are available from the National Earth System Science Data Center (2020, <http://www.geodata.cn/data/datadetails.html?dataguid=5881257&docid=19673>). The modern meteorological data are available from the China Meteorological Data Service Center (2021, http://data.cma.cn/en/?r=data/detail&dataCode=SURF_CLI_CHN_MUL_DAY_CES_V3.0).

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