How could phenological records from the Chinese poems of the Tang and Song Dynasties (618-1279 AD) be reliable evidence of past climate changes?

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Abstract. Phenological records in historical documents have been proved to be of unique value for reconstructing past climate changes. As a literary genre, poetry reached its peak period in the Tang and Song Dynasties (618-1279 AD) in China, which could provide abundant phenological records in this period when lacking 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 were discussed: (1) two principles namely the principle of conservative and the principle of personal experience should be followed to reduce the uncertainties; (2) the phenological records in poems need to be filtered according to the types of poems, the background information, the rhetorical devices, the spatial representations and the human influence; (3) the animals and plants are identified to species level according to their modern distributions and the sequences of different phenophases; (4) the phenophases in poems are identified on the basis of modern observation criterion; (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 Area of China were extracted to reconstruct the annual temperature anomalies in specific years of the period of 600-900 AD. Then 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 proved that the phenological records from

poems could be useful evidence of past climate changes after being scientifically processed and also provides a reference in both principle and methodology for the extraction and application of phenological records from poems not only for the study area and period in this study but also for larger areas and different periods in Chinese history.

Keywords. phenological records, poems, processing method, past climate changes, the Tang and Song Dynasties

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 over 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 reconstruct 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 AD) (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 the sources produced by institutions and the sources generated by individuals. The former includes Chinese classical documents, local gazettes, the archives of the Qing Dynasty (1644-1911 AD) and the Republic of China (1912-1949 AD) (Ge et al., 2008). Based on the documents produced by institutions, abundant phenological records have been extracted to reconstruct the past climate change of 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 et al., 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 snows) and “frost phenology” (the dates of first and last frosts). The limited amounts of organic phenophases in these documents are principally “agricultural phenology” (e.g., the beginning dates of spring cultivation, winter wheat harvest in summer and millet harvest in autumn). Therefore, the phenological data from documents produced by institutions can hardly be compared with those from modern observations, which majorly focus on the seasonal changes of natural plants. In contrast, the phenological information in personal documents (mostly refers to private diaries) are much more varied, which include quantities of 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 reconstructed the 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). In spite of these efforts, the diaries were most abundant within the past 800 years, especially in the Ming Dynasty (1368-1644 AD), the Qing Dynasty and the Republic of China, and the earliest diary found in China so far (The Diary of Genzi-Xinchou by Lv Zuqian) merely dated back to 1180 AD (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 relatively open society in the Tang and Song dynasties (618-1279 AD). 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 highest level during the Tang and Song Dynasties in ancient China. People from the emperors to the civilians in the Tang and Song Dynasties preferred to record their thoughts and daily lives in poems. Abundant phenological information that was described in the 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 in the starting and ending time, the regional differences and the degrees of warmth 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 WMP 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 massive 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 extracting phenological records from poems due to the usages of rhetorical devices, the limitations on poetic rules and forms as well as the needs of rhymes and sounds in the poems. In addition, the phenological evidence in the poems did not always follow the modern criterion, which would yield 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. In his study, 17 pieces of evidence were from poems and 11 of them were phenological information of the Tang and Song Dynasties. Although a few following studies (Man, 1998;Ge et al., 2010) has adopted phenological evidence from poems to reconstruct climate changes, further systematical 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 introduced the characteristics of phenological information in poems, including its accessibility and inherent uncertainties. Subsequently, we put forward basic principles and key processing steps for extracting phenological records from poems of the Tang and Song Dynasties. We also compared phenological records from poems with other proxies in the reconstructions of past climate changes in the Guanzhong Area 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 in both theory and method 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 record, poetry has both certainties and uncertainties in the application of past climate changes. For example, in the study of 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 demonstrate the certainties of phenological records from poetry. However, other phenological evidence such as the orange trees in the Guanzhong Area used by Chu (1973) may have uncertainties. For instance, some studies have pointed out that the orange trees in the Guanzhong Area recorded in the poems of the Tang Dynasty (618-907 AD) 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 analysed before being used in past climate change studies.

2.1 The certainties of phenological information from poems

Poetry is one of the major genres of Chinese literature. It expresses peoples' social life and spiritual world with concise words and abundant emotions 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 the treasure of Chinese traditional literature. People in the Tang and Song Dynasties preferred recording and sharing their lives and ideas via poems, which is similar to recording diaries in the later dynasties. Phenology, which could be used to indicate seasons and guide agricultural activities, is one of the favourite contents recorded by poets in their poems. 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 present were written by well-educated scholars, who were able to describe the phenological phenomena they saw without abusing the words. Thus, poetry is an excellent carrier of phenological information.

Regarding 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, which contain almost all kinds of phenological records, including organic ones and non-organic ones (Table 1). The realistic poems strive for the typicality in images, the authenticity in details and the objectivity in descriptions. For example, there is a line in a poem by Bai Juyi: "There is a crescent moon on the third night and the cicada sings for the first time"[1], which detailedly recorded 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, which can be an available data source for reconstructing past climatic changes.

2.2 The numbers, spatial distributions and accessibility of phenological records from the poems

By their very nature, the Chinese poems have many distinctions in the field of keeping phenological information with 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 & Archives of Peking University, 1999), nearly 50 thousand poems from the Tang Dynasty and more than 270 thousand poems from the Song Dynasty are preserved. Numerous phenological records in the poems not only include non-organic events, but also include a variety of organic phenomena, most of which are phenology of natural plants and animals.

The spatial distributions of the phenological records are highly consistent with the ruling regions of the dynasties and they show the characteristics of more records in more developed areas. Take the Song Dynasty (960-1279 AD) as an example. As north China was dominated by the Jin Dynasty from 1127 to 1279 AD, the phenological records from Quan-Song-Shi of this period are mainly located in southern China, especially around the city Hangzhou (the capital city of the Song Dynasty at that time).

In general, the accessibility of phenological records of poems is relatively lower than that of other documents. Unlike documents produced by institutions in which phenological evidence was recorded by dedicated persons, the phenological evidence in poems was recorded more inadvertently. The information of 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 has been 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 of poems may vary with different features of 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 two times greater than that of Li Bai. Only by integrating the same phenophase recorded by different poets could improve frequency and continuity.

2.3 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 have inherent uncertainties during the identification of species, the identification of phenophases, and the ascertainment of dates and sites, which should be excluded before using the phenological records to reconstruct past climate changes.

2.3.1 Uncertainties in the identification of species

Since the Chinese language has not changed fundamentally during the long history, the people in present day can read ancient poems almost without too much difficulty. Nevertheless, the changes in meanings and expressions of particular words and phrases still exist. Some words or phrases may have several additional meanings in ancient Chinese compared with 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 at present. For example, the Si sheng du juan (*Cuculus micropterus*) have at least three different names during the Tang and Song Dynasties (Table 4). It was also noticed 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.

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, so it is difficult to extract clear phenophases from poems. For example, there is a line in a poem by the poet Quan Deyu: "Peonies occupy the spring breeze with their fragrance alone"[12], which describes the phase of peonies flowering. However, the phenophase in this line is equivocal due to the use of personification. In order 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

The exact date is the crucial factor 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 have precise temporal information. For example, the poet Bai Juyi recorded in his poem: "The azalea is falling and the cuckoo is singing in this year"[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 April 30, 816 AD). However, the writing time was not consciously kept for most other poems. Any lack of information of year, month, or day may lead to failures in phenological and climatic reconstructions. For instance, Bai Juyi recorded in his another poem: "People are busy in the fifth lunar month because the wheat is yellow in the field."[14] Here, only the information of the month was directly presented in this poem, which would probably cause uncertainties when deducing the year and the day. To make matters worse, some poems were even not improvised, but were written according to the memories or imaginations of poets. The information from this kind of poems required to be excluded.

2.3.4 Uncertainties in ascertainment of sites

By matching the ancient name of a site with the modern one, the phenophases in the poems can be compared with the corresponding observational phenophases at the same site. However, similar to date, the sites of phenophases in poems are sometimes missing. Even worse, some names of the sites mentioned in the poems are imagined to express the emotions rather than to record real locations. For example, Lu You wrote a verse in his poem: "There are so many willow branches in Ba Qiao, but who would have thought sending one to me?"[15] Ba Qiao is a location in Xi'an (a city in central China), which is more than 700 km away from the place Lu You wrote this poem (Chengdu, China). By describing the willow branches in his hometown in this poem, the poet expressed his homesickness. When ascertaining the sites, these kinds of uncertainties should be carefully dealt with.

3 The Methods of Processing Phenological Records in Poems from the Tang and Song Dynasties for past climate studies

In order to minimize the uncertainty during the extraction of clear species, phenophase, date and site information from poems and to make them comparable with modern observations, several basic principles and processing steps should be put forward.

3.1 The basic principles for data processing

3.1.1 The principle of conservative

The principle of conservative refers to deducing the ambiguous information conservatively, so as to keep the characteristics of phenological information without causing too much deviation. Take the aforementioned poem of Bai Juyi[14] as an example, the poem was written in 807 AD in Xi'an according to background information while the exact date is not recorded. From the poem, we can know that the harvest date of wheat in that year appeared in the fifth lunar month (from June 10 to July 8 in the Gregorian calendar), so that the date of June 10 which is the closest to the modern observations (from May 26 to June 8 with the average of June 2) can be determined as the date of wheat harvest in 807 AD in Xi'an. It should be noted that if the recorded period in the poem is overlapped with the time of the modern phenophase, the principle of conservative 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 the records based on imaginations or memories. For example, Yang Wanli recorded a line in his poem: "Begonias in my hometown are flowering on this date and I see them booming in my dream."[16] From the line, we can easily know that he was not in his hometown when he wrote this poem. Thus, the phenophase of Begonia in this poem can not be used. It takes effort to diagnose the information in some poems. For example, Lu You wrote a poem in 1208 AD: "The Begonias in Biji Fang (place name) are the best in the world. Each branch looks dyed with scarlet blood."[17] By looking up into the life experience of Lu You, this poem is found to record his memory in 1172 AD. Therefore, this piece of record also can not be used as the phenological evidence according to the principle of personal experience.

3.2 The key steps of data processing

On the basis of the principles, four steps are required for the processing of phenological records in poems (Figure 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 who 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 to extract phenological records 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 effectiveness of phenological evidence. For example, there is a line of Su Shi saying: "A few branches of peach blossom outside the bamboo grove, and the ducks will notice the warming of the river firstly."[18] From this line, it seems to describe the natural phenophases in spring. However, by looking into the background information, we know that this poem is an illustrated poetry in painting. Therefore it describes the scenery within the painting instead of real nature. The record requires to be excluded.

(3) Filtering the records according to the rhetorical devices

Whether the use of rhetorical devices in poems may affect the authenticity of phenophases is required to be distinguished. For instance, despite the rhetorical device of personification used in the aforementioned poem by Quan Deyu[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: "The water in Laizhou (place name) has become shallower several times and how ripe is the peach fruit?"[19] seems to ask the time of peach phenophase, but actually, it is the quotation of the myths that the peaches mature once every three thousand years in wonderland. The rhetorical device of quotation in this line has affected the authenticity of phenophases. Thus, this piece of record should be eliminated.

(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: “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.”[20] This piece of record can not be directly compared with modern observational data because the difference in altitude is almost 1000 meters between the mountain in the poem and the modern observation site on the plain. Other factors that contribute to spatial differences such as valley, depression and heat island effect are also used to filter the records.

(5)Filtering the records according to the human influence

Human activities, such as cultivation and transplantion could also affect the phenophases of plants. In order to accurately reflect climate changes, it was 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 couldn’t live through winter normally in the Guanzhong Plain. Thus, they were majorly managed by humans. This kind of phenological information in poems cannot be used as indicators of climate changes.

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

There are mainly two ways to identify the animals and plants in poems from genera level to species level. The first way is to identify 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.”[21] This poem was written in Xi’an, which is located in the middle reaches of the Yellow River. In history, the species of peach were mainly *Amygdalus davidiana* and *Amygdalus persica*. According to modern species distribution, the former species distributes along the middle and lower reaches of the Yellow River while the latter distributes 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: “The green-up of willow leaves and the ume blossoms can’t stop me from being sad.”[22] The plant ume in ancient Chinese language usually refers to *Chimonanthus praecox* or *Armeniaca mume*. From the text content, we can infer that the ume blossoms was close in time with leaf expansion of willow. According to modern observation data in Chengdu, the average full leaf expansion date of willow (*Salix babylonica*) is on February 23, while the average full flowering date of *Chimonanthus praecox* and *Armeniaca mume* are January 10 and February 10, respectively. The average date of full flowering date 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 the 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). Take the aforementioned poem of Quan Deyu[12] as an example, the line described 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", "fallen" etc, the description of peony blooming in this poem was most likely to match with the full flowering date under the modern criteria "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 the time information, including clear year, month and date of the phenophase, from the titles, prefaces and lines of the poems. Then, for the missing time information, it could be deduced by consulting the background information, related studies or estimated reasonably according to the principle of conservative. Finally, the time information in the Chinese lunar calendar needs to be converted into the modern Gregorian calendar. For example, the poet Cui Riyong recorded in his poem: "The ume blossoms in the palace smell fragrant and look delicate with the background of snow."[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 7th day of the first lunar month). From the poem, we did 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 AD. Hence, we can know that this poem was written in 730 AD.

Similarly, the exact location of the sites could be confirmed. It should be noted to check whether the place names appearing in the poems are real sites for phenophases. For example, Ba qiao is not the site of phenophase for willow in the aforementioned poem by Lu You[15]. Thus, the record in this poem can not be used as the phenological evidence for past climate studies.

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

In order to test the reliability of phenological records in poems for past climate change studies and the validity of the processing methods mentioned in this study, we extracted 86 phenological records (appendix A) from the poems of the Tang Dynasty to reconstruct the mean annual temperatures in the Guanzhong Area of China during the period of 600-900 AD.

4.1 Study area

The Guanzhong Area (33°35′-35°50′N, 106°18′-110°37′E), located in central China (Figure 2), was where the capital city of the Tang dynasty was located. Many poets were active here and had left many poems describing phenology during the Tang dynasty. The study area has a continental monsoon climate with mean annual temperatures ranging from 7.8 ℃ to 13.5 ℃ and mean annual precipitation from 700 mm in the southwest to 500 mm in the northeast (Qian, 1991).

4.2 Data and methods

Since the 86 records from poems belong to diverse phenophases, they indicate temperature changes at different periods of the year. In order 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. Then the transfer functions were applied to reconstruct the annual temperature anomalies (with the reference period of 1961-1990 AD) in the Guanzhong Area during 600-900 AD. The modern phenological and meteorological data used and the detailed methods of the transfer functions were shown in appendix B.

4.3 Results and the comparisons with other reconstructions

Figure 3(a) shows the reconstructed annual temperature anomalies by the phenological records from poems. In order to prove their validations, the results were compared with relevant studies. The first series used for comparison is reconstructed by Liu et al (2016), which reconstructed the winter half-year (from October to next April) temperature anomalies by 87 phenological records from historical documents (mostly produced by institutions) for the period of 600-902 AD in the Guanzhong Area. The reconstruction by Liu et al (2016) is a reliable reference not only because of the same study area and period, but also because the proxies of the two studies were 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 the annual temperature anomalies (Figure 3(b)).

Table 6 shows the historical data sources, types and the numbers of phenological evidence in the study of Liu et al. (2016) and in this study. Except for one piece of record from poem (No. 13 in appendix A), there is no duplication in the other records between the two studies. In general, the two studies have similar amounts of evidence, while the data types of 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 of them (more than 77%) are non-organic phenophases or agricultural phenophases (Figure 3(b)). On the contrary, the majority (more than 96%) of evidence from poems in this study are phenophases of wild plants (Figure 33(a)). These differences prove that the phenological records in poems are effective supplements to historical phenological evidence both in quantities and types for the period of Tang Dynasty. It is also worth noting that the numbers of years reconstructed in this study (36) is relatively less than that based on the records in Liu et al. (2016) (76), further demonstrating 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 added for the comparisons. 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) (Figure 3(c)). The second was annual temperature anomalies reconstructed from tree rings in Asia (Ahmed et al., 2013) (Figure 3(d)). All the four reconstructions indicated that there were more relatively colder years in the later periods after around 800s. And the coldest years of the four reconstructions all occurred in this period. Before 800s, all the reconstructions by Liu et al. (2016), Ge et al. (2003) and our study showed more relatively warmer temperatures while the warmest years were focused around 660s. Furthermore, the amplitude of reconstructed temperature by Liu et al. (2016) was 3.30 ℃, which was very similar to the amplitude of reconstructed temperature (3.28 ℃) by our study and modern (3.97 ℃ with respect to 1951-2013). All these similarities of different reconstructions confirm the effectiveness of phenological records from poems for past climate changes.

5 Discussions

There are still controversies on how climate changes in 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, pollens, and sediments (Xu et al., 2004;Zhang et al., 2014;Zhu et al., 2019), their results either cannot cover the whole period or they have relatively low temporal resolutions. In addition, these natural proxies are mostly collected from uninhabited areas, thus they can hardly be used for further 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 the climate change 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 various phenological information, which will undoubtedly contribute to the study of historical climate change.

Despite this, very few studies so far have been reported to use phenological records from poems to reconstruct historical climate change quantitatively due to the lack of effective methodology 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 requires only counting the number of annual rings from the outside to the inside or comparing them with a standard chronology. However, the temporal information in the poems cannot be obtained directly from a reference chronology. As already mentioned, the temporal information in the poems may be hidden in the poet's biography, the official history book, 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, even if some information is found to be unrecorded after searching through large amounts of materials. The problem also exists when extracting the information of 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, filter the useless records efficiently. By following the principles and steps, researchers are able to know where to find the information needed and how to deal with the phenological data from poems. The extracted phenological records are comparable with modern observation data and can be used as the proxy for reconstructing the climate changes quantitatively.

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 beyond this study. On the one hand, many studies have demonstrated that climate is the primary driving factor of phenophases in whole China (Piao et al., 2006;Dai et al., 2014;Ge et al., 2015;Tao et al., 2017), which indicate that the phenological records obtained at any place can be used as the evidence of climate changes. On the other hand, historians all agree that the feudal society in Chinese history had not fundamentally changed during different dynasties (Liu, 1981;Tian, 1982;Feng, 1994). Although historical China varied its administrated area coverage from dynasty to dynasty, its core social-economic closely aligned with the major agricultural area throughout history. This geographic and temporal overlap allows for continuous comparison across the Chinese core areas (Fang et al., 2019). Correspondingly, the essence of literature, especially poetry, has not changed, though different dynasties may have various popular trends of poetry such as the limitations on poetic forms, the number of words, the needs of rhymes and sounds etc. Therefore, the pheological records obtained from poems of different periods in core areas of historical China can also be extracted and processed for climatic reconstruction according to the method in this study.

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 were shown in Appendix C, there are other uncertainties that is difficult to be assessed quantitatively. For example, the differences of 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 mainly driven by climate changes, especially temperature variations (Estrella et al., 2007;Lobell et al., 2012;Liu et al., 2018). Despite this, the reconstruction in the study is a case to prove the reliability of the phenological records from poems in indicating past climate changes. In fact, there are still plenty of phenological records that are not extracted. By rough estimation, the temporal resolution of the phenological records from poems of the Tang and Song Dynasties can reach at least 20 years. 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 AD) as an example. Although north China was dominated by the Jin Dynasty from 1127 to 1279 AD, which results in most poems written by the poets living in north 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 contemporary phenological records in north China. The rich records around the capitals and developed cities are of great value in comparison 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 change and climate change over a large 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 conservative 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 the human influence; (2) identifying the animals and plants to species level; (3) judging the phenophases according to the modern observation criteria; (4) ascertaining the time and sites. Then, we used this method to extract 86 phenological records from the poems of the Guanzhong Area in central China and reconstructed the annual mean temperature anomalies for specific years during 600-900 AD. 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 provides a reference in both theory and method for the extraction and application of phenological records from poems in the studies of past climate changes.

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 the original and sources of the verses used in this paper are listed in Appendix D in Chinese. The modern phenological data are available from the National Earth System Science Data Center(2020). The modern meteorological data are available from the China Meteorological Data Service Center (2020).

Author contributions.

Yachen Liu and Zexing Tao contributed to the idea and design of the structure of paper; Yachen Liu collected and analysed the data; Yachen Liu, Qiuqi Fang, Junhu Dai, Huanjiong Wang and Zexing Tao wrote the paper.

Competing interests.

The authors declare that they have no conflict of interest.

Special issue statement.

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Figures and tables

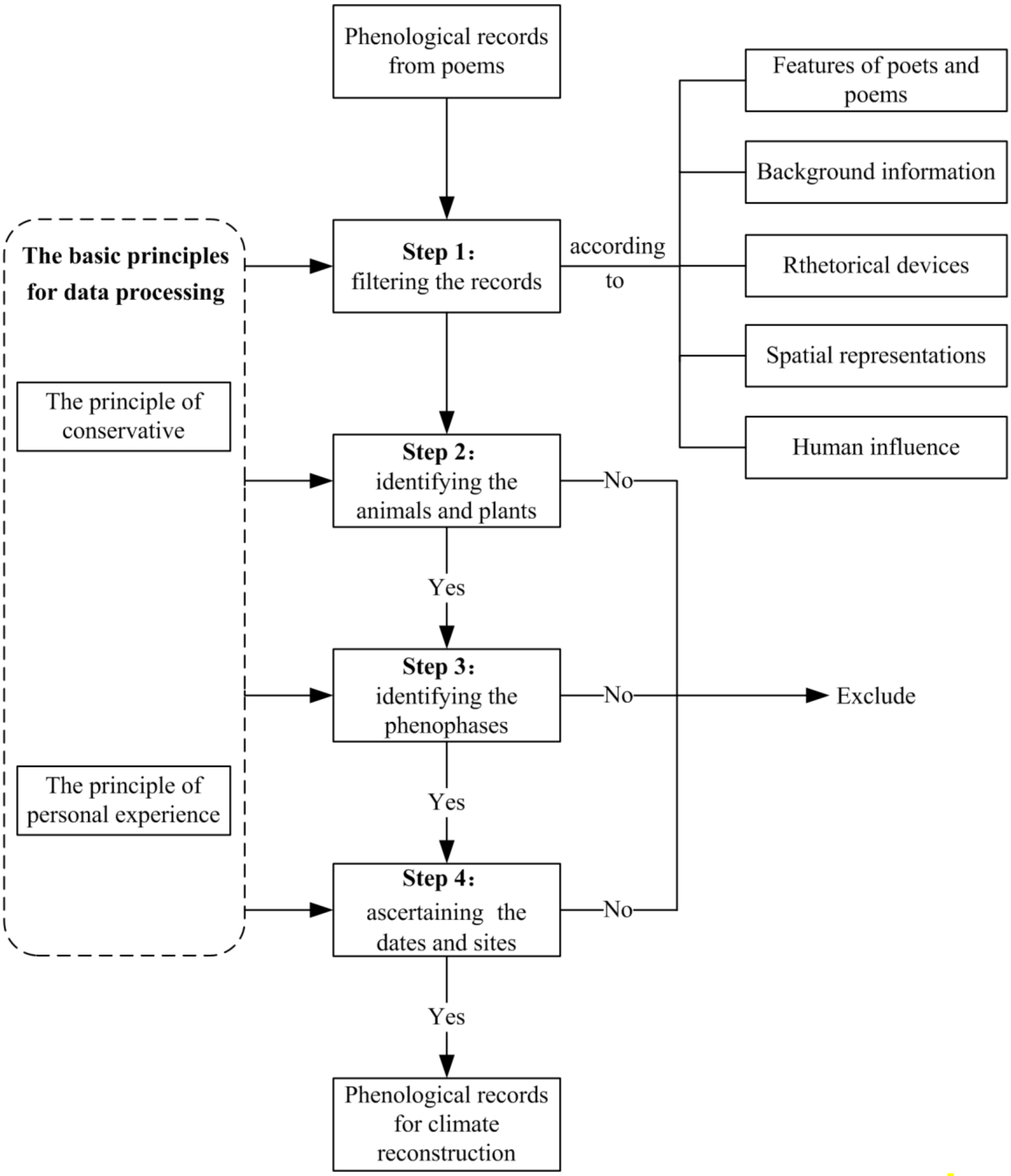

Figure 1 Processing steps of phenological records in poems for climate reconstructions.

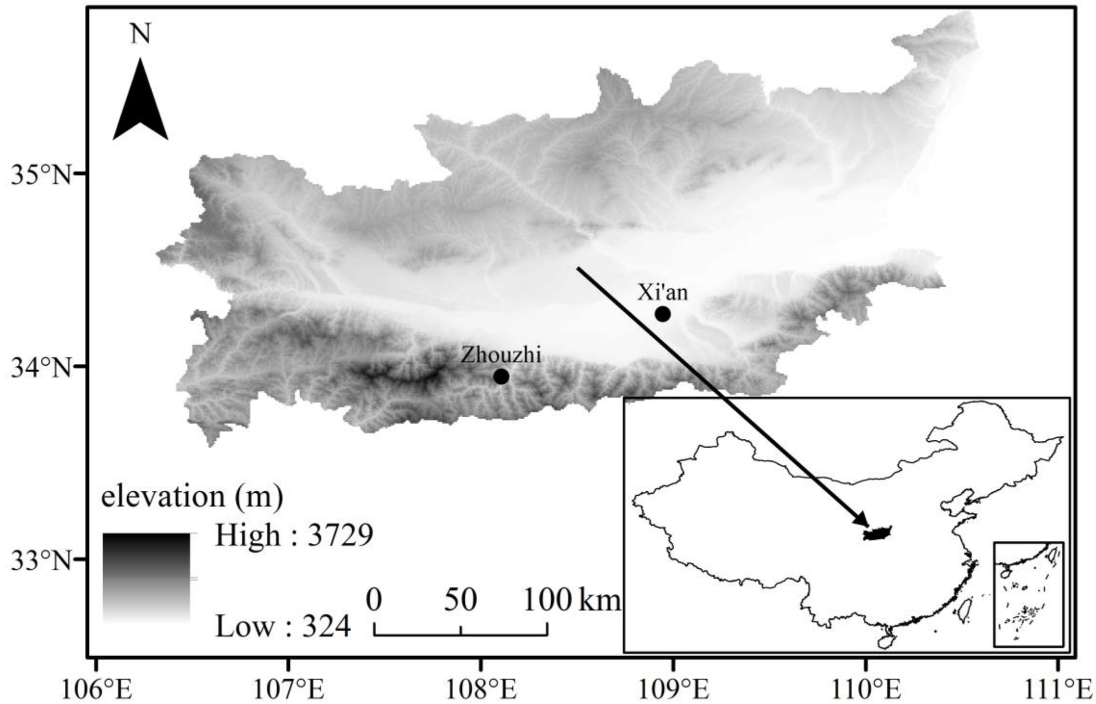

Figure 2 The location of the Guanzhong Area for the climatic reconstructions in this study with the modern names of sites mentioned in the poems.

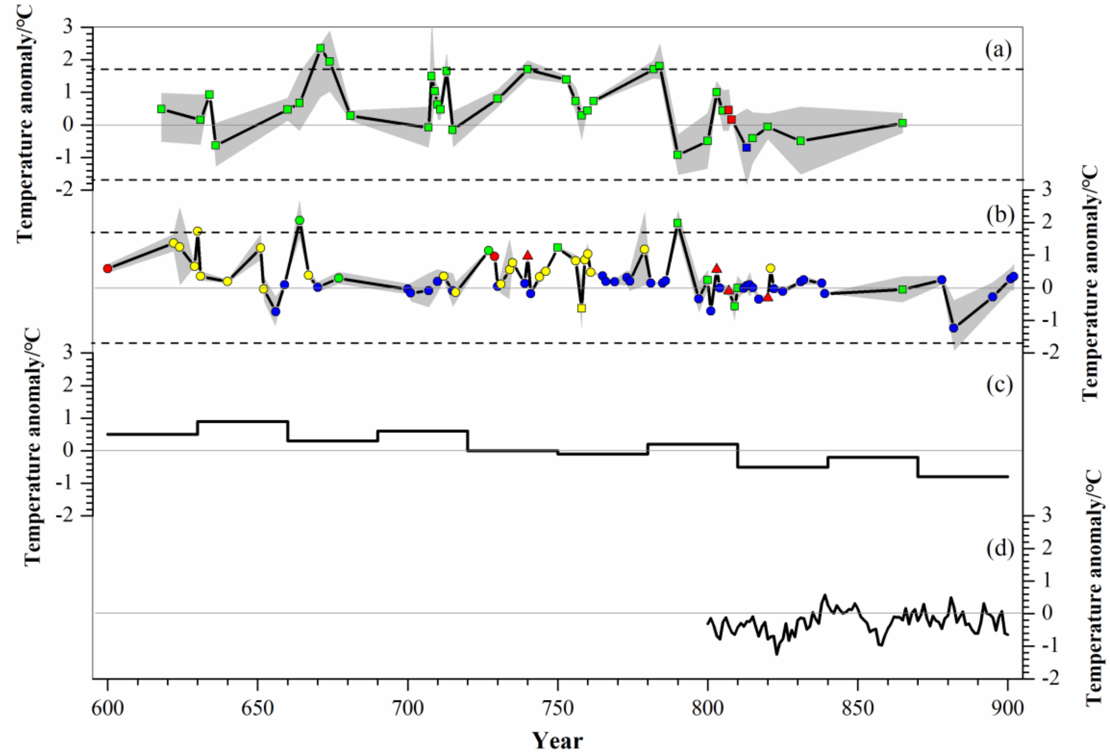

Figure 3 Comparison of reconstructed temperature anomalies for 600-900 AD (with respect to the mean climatology between 1961 and 1990). (a): The annual mean temperature anomalies

reconstructed by phenological records from poems in this study; (b): The annual mean temperature anomalies reconstructed using the phenological records from historical documents by Liu et al. (2016); (c): The 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). (d): The annual mean temperature reconstructed from tree rings for whole Asia by Ahmed et al. (2013). The squares: temperature anomalies reconstructed from poems; The circles: temperature anomalies reconstructed from documents of institutions; The triangles: temperature anomalies reconstructed from both poems and documents of institutions; The color green: temperature anomalies reconstructed by phenophases of wild plants; The color yellow: temperature anomalies reconstructed by agricultural phenophases; The color blue: temperature anomalies reconstructed by non-organic phenophases; The color red: temperature anomalies reconstructed by at least two types of phenophases; The gray area approximates the 95% confidence interval completed from linear regression error. The dotted lines indicate the 2 standard deviation range of 1.72 ℃ of modern period (1951-2013).

Table 1 The different types of phenology in the poetry of the Tang and Song Dynasties.

Types of phenology		Examples of poems
Non-organic	phenology of ice	All the springs are frozen and stagnant[2]
	phenology of snows	It snows in the 8th lunar month in frontier regions[3]
	phenology of frosts	Frost falls in the 8th lunar month of every year[4]
Organic	phenology of agriculture	The poople have just finished planting mulberry trees to raise silkworms and they are going to transplant rice seedling again[5]
	phenology of natural plants	Ume blossoms begin to bloom in early winter[6]
	phenology of animals	The river reflects the autumn scenery and the geese begin to fly south[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)	most non-organic(phenology of ice, snow and frost) and a few organic(agricultural phenology)
Numbers 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/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/ species-specific clear	ambiguous/species-specific clear	most clear
Phenophases clarity	ambiguous/phenophase-specific clear	ambiguous/phenophase-specific clear	most clear
Spatial clarity	ambiguous/inferable	clear/inferable	most clear
Temporal clarity	ambiguous/inferable	clear/inferable	most clear

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

Pinyin of the verses	The meanings of "jin hua" in the poems
fan ci huang **jin hua**[8]	chrysanthemum (inferred from context)
sheng li **jin hua** qiao nai han[9]	decorations on ladies' headwear
xuan miao mei **jin hua**[10]	an alchemistic term for Taoist priests
cui wei **jin hua** bu ci ru[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 names	Pinyin of modern names	Latin names
Animals	Si jiu, Zi gui, Du yu	Si sheng du juan	*Cuculus micropterus*
	Cang geng, Shang geng, Chu que, Huang niao	Hei zhen huang li	*Oriolus chinensis*
	Xuan niao, Yi niao, Luan niao, Tian nv, Wu yi	Jia yan	*Hirundo rustica*
	Tiao, Fu yu, Ni, Qi nv	Cao chan	*Mogannia conica*
Plants	Fu qu, Fu rong, Han dan	Lian	*Nelumbo nucifera*
	Lu, Wei, Jian jia	Lu wei	*Phragmites australis*
	Shan shi liu, Ying shan hong, Shan zhi zhu	Du juan	*Rhododendron simsii*
	Mu li, ming zha, Man zha	Mu gua	*Chaenomeles sinensis*

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

Phenophases	Translations of the original verses	Descriptions in the modern observation criteria
First song	New cicada tweeted two or three times[23]	The date of first call

First appearance	New swallow came ten days before the festival of She[24]	The date of first appearance
First leaf	Willow leaves are tender just like a beauty frown slightly[25]	The date when the first one or two leaves are spread out
Full leaf expansion	The green lotus leaves stretch to the horizon[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 they cover the palace[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[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[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[28]	The date when *Salix* spp. and *Populus* spp. begin to have fluffy catkins

Table 6 The 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

Appendix A: The phenological records from poems used in the reconstruction of this study.

No.	Gregorian dates	Sites	Phenophases	Translations of the original verses
1	28 June 618	Xi'an	End flowering date of *Punica granatum*	It missed the spring because of late blooming.[30]
2	27 February 631	Xi'an	Full leaf expansion date of *Salix babylonica*	The leaves of willow welcome the third lunar month and the ume blossoms take the two years apart.[31]
3	27 February 631	Xi'an	Full-flowering date of *Armeniaca mume*	The leaves of willow welcome the third lunar month and the ume blossoms take the two years apart.[31]
4	18 January 634	Xi'an	Full-flowering date of *Chimonanthus praecox*	There are no leaves on the willow tree, but flowers on the ume tree.[32]
5	27 April 636	Xi'an	Full-flowering date of *Juglans regia*	Peach flowers blossom for those who are going away.[33]
6	10 September 660	Xi'an	Full-flowering date of *Osmanthus fragrans*	Only osmanthus blooms near the south hill.[34]
7	31 August 664	Xi'an	End flowering date of *Osmanthus fragrans*	Osmanthus is at the end of flowering in the moonlight and the ume tree is at the beginning of flowering under the beam.[35]
8	31 August 664	Xi'an	First flowering date of *Chimonanthus praecox*	Osmanthus is at the end of flowering in the moonlight and the ume tree is at the beginning of flowering under the beam.[35]
9	8 February 671	Xi'an	First flowering date of *Armeniaca mume*	Ume blossoms early in the palace and the willow is new near the creek.[36]

10	8 February 671	Xi'an	First leaf date of *Salix babylonica*	Ume blossoms early in the palace and the willow is new near the creek.[36]
11	18 February 674	Xi'an	Full leaf expansion date of *Salix babylonica*	The wicker swings to show its beauty.[37]
12	11 August 681	Xi'an	Fruit maturity date of *Amygdalus davidiana*	The peaches in the palace are very luxuriant.[38]
13	6 April 707	Xi'an	End flowering date of *Amygdalus davidiana*	The flowers of peach are going to fall while the branches of willow are stretching.[21]
14	6 April 707	Xi'an	Full leaf expansion date of *Salix babylonica*	The flowers of peaches are going to fall while the branches of willow are stretching.[21]
15	4 February 708	Xi'an	First leaf date of *Salix babylonica*	The delicate wicker on the embankment has not turned yellow.[39]
16	4 February 708	Xi'an	First flowering date of *Armeniaca mume*	The fragrance of ume blossoms and the color of willows can withstand praise.[40]
17	4 February 708	Xi'an	First leaf date of *Salix babylonica*	The fragrance of ume blossoms and the color of willows can withstand praise.[40]
18	4 February r 708	Xi'an	First flowering date of *Armeniaca mume*	The fragrance of ume blossoms seems to be obscured by beautiful singing.[41]
19	4 February 708	Xi'an	First flowering date of *Armeniaca mume*	Ume blossoms vie to bloom in the palace.[42]
20	4 February 708	Xi'an	First flowering date of *Armeniaca mume*	The ume blossoms and willows in the palace can recognize the

				weather.[43]
21	4 February 708	Xi'an	First leaf date of *Salix babylonica*	The ume blossoms and willows in the palace can recognize the weather.[43]
22	4 February 708	Xi'an	First flowering date of *Amygdalus davidiana*	Why do peaches and plums compete to bloom.[44]
23	4 February 708	Xi'an	First flowering date of *Prunus salicina*	Why do peaches and plums compete to bloom.[44]
24	4 February 708	Xi'an	First flowering date of *Armeniaca vulgaris*	New apricot blossoms adorn the palace and ume blossoms bloom at the feast.[45]
25	4 February 708	Xi'an	First flowering date of *Armeniaca mume*	New apricot blossoms adorn the palace and ume blossoms bloom at the feast.[45]
26	10 February 709	Xi'an	Full-flowering date of *Chimonanthus praecox*	The flicking of snow on the branches adds to the beauty of ume blossoms. [46]
27	21 February 709	Xi'an	First flowering date of *Armeniaca mume*	Ume blossoms and willow catkins are new.[47]
28	15 March 709	Xi'an	Full leaf expansion date of *Salix babylonica*	The willows leaves are all open over the city.[48]
29	15 March 709	Xi'an	Full leaf expansion date of *Salix babylonica*	Willows secretly urge the late spring.[49]
30	17 April 709	Xi'an	Beginning date of fruit drop of *Salix babylonica*	The willow by the river flicks the emperor's goblet.[50]
31	16 October 709	Xi'an	End flowering date of *Osmanthus fragrans*	The osmanthus fell into the goblet full of wine.[51]
32	4 March 710	Xi'an	Full-flowering date of *Armeniaca mume*	The ume blossoms remain white when the cold is over while the

				willows have not turned yellow when the wind is late.[52]
33	4 March 710	Xi’an	Full leaf expansion date of *Salix babylonica*	The ume blossoms remain white when the cold is over while the willows have not turned yellow when the wind is late.[52]
34	4 March 710	Xi’an	Full leaf expansion date of *Salix babylonica*	There are thousands of willows unfolding their leaves.[53]
35	25 March 710	Guanzhong	Full-flowering date of *Amygdalus davidiana*	There are red flowers all over the ground and the whole banquet is filled with fragrance.[54]
36	25 March 710	Guanzhong	Full-flowering date of *Amygdalus davidiana*	The red calyxes bloom against the dawn in the garden.[55]
37	25 March 710	Guanzhong	Full-flowering date of *Amygdalus davidiana*	The peach blossoms are bright and seem to have brilliance.[56]
38	25 March 710	Guanzhong	Full-flowering date of *Amygdalus davidiana*	Countless flowers bloom among the flowers by the water.[57]
39	25 March 710	Guanzhong	Full-flowering date of *Amygdalus davidiana*	The gorgeous flowers in the garden accompany the beauty.[58]
40	3 April 710	Guanzhong	End flowering date of *Amygdalus davidiana*	The peach blossoms by the Wei River fall into the water.[59]
41	4 April 710	Xi’an	Full-flowering date of *Amygdalus davidiana*	When the peaches and plums bloom in spring, the scenery of the capital city is good.[60]
42	4 April 710	Xi’an	Full-flowering date of *Prunus salicina*	When the peaches and plums bloom in spring, the scenery of the capital city is good.[60]
43	4 April 710	Xi’an	Beginning date of fruit drop of *Salix babylonica*	The red calyx exudes fragrance and the branches of willows are

				surrounded by green ribbons.[61]
44	4 April 710	Xi'an	Full-flowering date of *Amygdalus davidiana*	The red calyx exudes fragrance and the branches of willows are surrounded by green ribbons.[61]
45	5 April 710	Xi'an	End flowering date of *Armeniaca mume*	The ume blossoms in the palace glowed against the snow and the willow trees in the city were full of smog.[62]
46	5 April 710	Xi'an	Beginning date of fruit drop of *Salix babylonica*	The ume blossoms in the palace glowed against the snow and the willow trees in the city were full of smog.[62]
47	5 April 710	Xi'an	Beginning date of fruit drop of *Salix babylonica*	The willows and ume blossoms in the palace are covered with green ribbons. [63]
48	5 April 710	Xi'an	End flowering date of *Armeniaca mume*	The willows and ume blossoms in the palace are covered with green ribbons. [63]
49	5 April 710	Xi'an	Beginning date of fruit drop of *Salix babylonica*	The willows are covered with green smog.[64]
50	6 April 710	Xi'an	Beginning date of fruit drop of *Salix babylonica*	The green ribbons from the willows float at the banquet.[65]
51	6 April 710	Xi'an	End flowering date of *Amygdalus davidiana*	Red peach blossoms and emerald green willows adorn the fete[66]
52	6 April 710	Xi'an	Beginning date of fruit drop of *Salix babylonica*	Red peach blossoms and emerald green willows adorn the fete.[66]
53	9 May 710	Xi'an	First flowering date of *Hibiscus syriacus*	Trees cover the palace and the hibiscuses start to turn red.[67]
54	24 March 711	Guanzhong	Full-flowering date of	The peach and plum blossoms are

			Prunus salicina	lost in their own fragrance.[68]
55	24 March 711	Guanzhong	Full-flowering date of *Amygdalus davidiana*	The peach and plum blossoms are lost in their own fragrance.[68]
56	14 February 713	Xi'an	End flowering date of *Chimonanthus praecox*	The garden is only accompanied by withered ume blossoms in spring.[69]
57	28 February 713	Xi'an	First leaf date of *Salix babylonica*	The branches of willows are fresh.[70]
58	7 April 715	Xi'an	End flowering date of *Amygdalus davidiana*	The pool water is covered with peach blossoms.[71]
59	29 January 730	Xi'an	Full-flowering date of *Chimonanthus praecox*	The ume blossoms in the palace smell fragrant and look delicate with the background of snow.[29]
60	3 April 740	Xi'an	Beginning date of fruit drop of *Salix babylonica*	People at the banquet all resent the falling catkins.[72]
61	10 April 753	Xi'an	Beginning date of fruit drop of *Salix babylonica*	The catkins fall like snowflakes.[73]
62	5 February 756	Xi'an	Full-flowering date of *Chimonanthus praecox*	The umes bloom towards the sky.[74]
63	18 March 758	Xi'an	First leaf date of *Salix babylonica*	There are thousands of tender branches of willows in the palace.[75]
64	18 March 758	Xi'an	Full-flowering date of *Amygdalus davidiana*	Peach blossoms are as red as drunk.[76]
65	15 April 758	Xi'an	End flowering date of *Amygdalus davidiana*	The peach blossoms wither after the catkins.[77]
66	15 April 758	Xi'an	Beginning date of fruit drop of *Salix babylonica*	The peach blossoms wither after the catkins.[77]
67	3 April 760	Xi'an	Full-flowering date of *Pyrus betulaefolia*	Pear flowers bloom during the Cold Food Festival.[78]
68	18 March 762	Xi'an	Full leaf expansion date of	Flowers and willows in every

			Salix babylonica	village bloom of their own accord.[79]
69	3 April 782	Xi'an	Beginning date of fruit drop of *Salix babylonica*	In spring the city is full of flying catkins.[80]
70	25 February 784	Xi'an	First leaf date of *Salix babylonica*	The flowers and willows in the capital are fresh.[81]
71	19 April 790	Xi'an	Full-flowering date of *Paeonia suffruticosa*	Peonies occupy the spring breeze with their fragrance alone.[12]
72	4 April 800	Xi'an	Beginning date of fruit drop of *Salix babylonica*	The sycamore blooms after the willow catkins.[82]
73	4 April 800	Xi'an	First flowering date of *Firmiana platanifolia*	The sycamore blooms after the willow catkins.[82]
74	4 April 800	Xi'an	First flowering date of *Amygdalus davidiana*	Peach and plum flowers are fresh in every courtyards.[83]
75	4 April 800	Xi'an	First flowering date of *Prunus salicina*	Peach and plum flowers are fresh in every courtyard.[83]
76	4 April 800	Xi'an	First flowering date of *Paulowinia fortunei*	Paulownia blooms on Qingming Festival.[84]
77	2 May 805	Xi'an	End flowering date of *Paulowinia fortunei*	The purple paulownia flowers are falling and the birds are singing.[85]
78	7 August 805	Xi'an	First sing date of *Cryptotympana atrata*	A new cicada calls two or three times.[86]
79	1 May 807	Zhouzhi	End flowering date of *Paeonia suffruticosa*	When I come back, the peony flowers are all over.[87]
80	10 June 807	Zhouzhi	Beginning date of winter wheat harvest	People are busy in the fifth lunar month because the wheat is yellow in the field.[14]
81	22 October 808	Xi'an	First date of frost	Frost falls in the ninth lunar month and it turns cold early in autumn.[88]
82	27 September 813	Xi'an	Full-flowering date of	The osmanthus beside the railing

			Osmanthus fragrans	exudes fragrance.[89]
83	13 May 815	Xi’an	Beginning date of fruit drop of *Salix babylonica*	Willow catkins are flying all over the sky just like snowflakes.[90]
84	3 April 820	Xi’an	Full-flowering date of *Armeniaca vulgaris*	Although the apricot blossoms here are better than in other places, I still want to see the flowers in my hometown.[91]
85	24 September 831	Xi’an	Full-flowering date of *Osmanthus fragrans*	The cold dew wet the osmanthus quietly.[92]
86	4 April 865	Xi’an	End flowering date of *Armeniaca vulgaris*	Apricot flowers seem to be sad with me together.[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 Area, 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 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 date of spring cultivation were defined as the first day when the daily mean temperature is consecutively higher than 5 ℃ for five days (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 ℃ for five days (Hao et al., 2009).

After changing the time series of temperature and phenophases to anomalies with respect to the reference period (1961–1990 AD), 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 square method, which represents 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: 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**	0.742
Last date of frost	y=-0.033x+0.386	53	-0.475**	0.724
First date of snow	y=0.010x-0.023	26	0.467*	0.321
Last date of snow	y=-0.006x-0.019	26	-0.335	0.336
First sing date of *Cryptotympana atrata*	y=0.013x+0.012	15	0.638	0.216
Beginning date of spring cultivation	y=-0.030x+0.232	62	-0.396**	0.792
Beginning date of winter wheat harvest	y=-0.084x+1.284	22	-0.570**	0.584
Beginning date of millet harvest	y=0.024x+0.336	61	0.231	0.806
First flowering date of *Amygdalus davidiana*	y=-0.075x+0.361	38	-0.573**	0.667

Full-flowering date of *Amygdalus davidiana*	y=-0.086x+0.331	38	-0.634**	0.630
End flowering date of *Amygdalus davidiana*	y=-0.069x+0.441	37	-0.531**	0.691
Fruit maturity date of *Amygdalus davidiana*	y=0.022x+0.740	13	0.495	0.505
First flowering date of *Armeniaca mume*	y=-0.044x+0.626	14	-0.436	0.785
Full-flowering date of *Armeniaca mume*	y=-0.055x+0.590	14	-0.507	0.752
End flowering date of *Armeniaca mume*	y=-0.061x+0.586	14	−0.617*	0.717
First flowering date of *Armeniaca vulgaris*	y=-0.029x+0.119	24	-0.320	0.467
Full-flowering date of *Armeniaca vulgaris*	y=-0.045x+0.196	20	-0.517*	0.402
End flowering date of *Armeniaca vulgaris*	y=-0.028x+0.135	24	-0.331	0.466
First flowering date of *Chimonanthus praecox*	y=-0.007x+0.669	26	0.196	0.845
Full-flowering date of *Chimonanthus praecox*	y=-0.011x+0.770	25	-0.218	0.813
First flowering date of *Firmiana platanifolia*	y=-0.016x+0.135	14	-0.217	0.486
First flowering date of *Hibiscus syriacus*	y=-0.014x+0.060	18	-0.457	0.456
Full-flowering date of *Juglans regia*	y=-0.076x+0.441	33	-0.663*	0.612
Full-flowering date of	y=-0.069x+0.306	17	-0.611**	0.716

Osmanthus fragrans				
End flowering date of *Osmanthus fragrans*	*y*=0.044*x*+0.486	22	0.497*	0.728
Full-flowering date of *Paeonia suffruticosa*	*y*=-0.088*x*+0.307	38	-0.703**	0.581
End flowering date of *Paeonia suffruticosa*	*y*=-0.065*x*+0.493	36	-0.446**	0.731
First flowering date of *Paulownia fortunei*	*y*=-0.062*x*+0.688	22	-0.607*	0.813
End flowering date of *Paulownia fortunei*	*y*=-0.055*x*+1.103	18	-0.382	0.901
First flowering date of *Prunus salicina*	*y*=-0.068*x*+0.585	13	-0.740**	0.515
Full-flowering date of *Prunus salicina*	*y*=-0.068*x*+0.591	13	-0.779**	0.480
End flowering date of *Punica granatum*	*y*=0.056*x*+0.257	21	-0.450	0.825
Full-flowering date of *Pyrus betulaefolia*	*y*=-0.076*x*+0.441	27	-0.698**	0.608
First leaf date of *Salix babylonica*	*y*=-0.052*x*+0.745	31	-0.471**	0.711
Full leaf expansion date of *Salix babylonica*	*y*=-0.042*x*+0.511	37	-0.384*	0.753
Beginning date of fruit drop of *Salix babylonica*	*y*=-0.091*x*+1.312	17	-0.707**	0.602

*: $P<0.05$, **: $P<0.01$

Appendix D: The original verses and sources of the poems in Chinese used in this paper.

1. “微月初三夜，新蝉第一声”（[唐]白居易《六月三日夜闻蝉》）；

2. “百泉冻皆咽，我吟寒更切”（[唐]刘驾《苦寒吟》）；

3. “北风卷地白草折，胡天八月即飞雪”（[唐]岑参《白雪歌送武判官归京》）；

4. “仍说秋寒早，年年八月霜”（[宋]司马光《晋阳三月未有春色》）；

5. “乡村四月闲人少，才了蚕桑又插田”（[宋]翁卷《乡村四月》）；

6. “梅信初传冬未深，高门熊梦庆相寻”（[宋]胡寅《吴守生朝》）；

7. “江涵秋影雁初飞，与客携壶上翠微”（[唐]杜牧《九日齐山登高》）；

8.“泛此黄金花，颓然清歌发”（[唐]李白《忆崔郎中宗之游南阳遗吾孔子琴抚之潸然感旧》）；

9. “尊前柏叶休随酒，胜里金花巧耐寒”（[唐]杜甫《人日两首其二》）；

10. “黄帝术，玄妙美金花”（[唐]吕岩《忆江南》其三）；

11. “赤霄玄圃须往来，翠尾金花不辞辱”（[唐]杜甫《赤霄行》）；

12.“澹荡韶光三月中，牡丹偏自占春风”（[唐]权德舆《和李中丞慈恩寺清上人院牡丹花歌》）；

13.“今年杜鹃花落子规啼，送春何处西江西”（[唐]白居易《送春归（元和十一年三月三十日作）》）；

14. “田家少闲月，五月人倍忙。夜来南风起，小麦覆陇黄”（[唐]白居易《观刈麦》）；

15. “灞桥烟柳知何限，谁念行人寄一支”（[宋]陆游《秋夜怀吴中》）；

16. “故园今日海棠开，梦入江西锦绣堆”（[宋]杨万里《春晴怀故园海棠二首》）；

17. “碧鸡海棠天下绝，枝枝似染猩猩血”（[宋]陆游《海棠歌》）；

18. “竹外桃花两三枝，春江水暖鸭先知”（[宋]苏轼《惠崇春江晚景》）；

19. “莱洲频度浅，桃实几成圆”（[唐]卢照龄《于时春也慨然有江湖之思寄赠柳九陇》）；

20. “人间四月芳菲尽，山寺桃花始盛开”（[唐]白居易《题大林寺》）；

21. “桃花欲落柳条长，沙头水上足风光。”（[唐]刘宪《上巳日祓禊渭滨应制》）；

22. “柳条弄色不忍见，梅花满枝空断肠”（[唐]高适《人日寄杜二拾遗》）；

23. “故人千万里，新蝉三两声”（[唐]白居易《立秋日曲江忆元九》）；

24. “要信今年春事早，社前十日燕新来”（[宋]陆游《新燕》）；

25. “学嚬齐柳嫩，妍笑发春丛”（[唐]许敬宗《奉和登陕州城楼应制》）；

26. “接天莲叶无穷碧，映日荷花别样红”（[宋]杨万里《晓出净慈寺送林子方》）；

27. “向浦回舟萍已绿，分林蔽殿槿初红”（[唐]沈全期《兴庆池侍宴应制》）；

28. “满街杨柳绿丝烟，画出清明二月天”（[唐]韦庄《鄜州寒食城外醉吟》）；

29.“曲池苔色冰前液，上苑梅香雪里娇”（[唐]崔日用《奉和人日重宴大明宫恩赐彩缕人胜应制》）；

30.“只为来时晚，花开不及春”（[唐]孔绍安《侍宴咏石榴》）；

31.“柳色迎三月，梅花隔二年”（[唐] 李百药《奉和初春出游应令》）；

32.“柳影冰无叶，梅心冻有花”（[唐] 李世民《冬日临昆明池》）；

33.“舒桃临远骑，垂柳映京营”（[唐]褚亮《奉和禁苑饯别应令》）；

34.“独有南山桂花发，飞来飞去袭人裾”（[唐]卢照邻《长安古意》）；

35.“月宫清晚桂，虹梁绚早梅”（[唐] 许敬宗《奉和过慈恩寺应制》）；

36.“上苑梅花早，御沟杨柳新”（[唐]骆宾王《西行别东台详正学士》）；

37.“柳色摇岁华，冰文荡春照”（[唐]卢照龄《七日登乐游故墓》）；

38.“梦梓光青陛，秾桃蔼紫宫”（[唐]刘祎之《奉和太子纳妃太平公主出降》）；

39.“映水轻苔犹隐绿，缘堤弱柳未舒黄”（[唐]马怀素《奉和立春游苑迎春应制》）；

40.“彩蝶黄莺未歌舞，梅香柳色已矜夸”（[唐]李显《立春日游苑迎春》）；

41.“梅香欲待歌前落，兰气先过酒上春”（[唐]卢藏用《奉和立春游苑迎春应制》）；

42.“林中觅草才生蕙，殿里争花并是梅”（[唐]沈佺期《奉和立春游苑迎春》）；

43.“剪绮裁红妙春色， 宫梅殿柳识天情”（[唐]崔日用《奉和立春游苑迎春应制》）；

44.“借问桃将李，相乱欲何如”（[唐]上官婉儿《奉和圣制立春日侍宴内殿出翦彩花应制》）；

45.“金阁妆新杏，琼筵弄绮梅”（[唐]宋之问《奉和立春日侍宴内出剪彩花应制》）；

46.“拂树添梅色，过楼助粉妍”（[唐]李峤《游禁苑陪幸临渭亭遇雪应制》）；

47.“今日回看上林树，梅花柳絮一时新”（[唐]赵彦昭《苑中人日遇雪应制》）；

48.“山花缇绮绕，堤柳幔城开”（[唐]沈佺期《奉和晦日驾幸昆明池应制》）；

49.“节晦蓂全落，春迟柳暗催”（[唐]宋之问《奉和晦日幸昆明池应制》）；

50.“野花飘御座，河柳拂天杯”（[唐]沈佺期《三日梨园侍宴》）；

51.“泛桂迎尊满，吹花向酒浮”（[唐]李显《九月九日幸临渭亭登高得秋字》）；

52.“寒尽梅犹白，风迟柳未黄”（[唐]宗楚客《正月晦日侍宴浐水应制赋得长字》）；

53.“千行发御柳，一叶下仙筇”（[唐]张说《侍宴浐水赋得浓字》）；

54.“绮萼成蹊遍籞芳，红英扑地满筵香”（[唐]李乂《侍宴桃花园咏桃花应制》）；

55.“红萼竞燃春苑曙，蓁茸新吐御筵开”（[唐]赵彦昭《侍宴桃花园咏桃花应制》）；

56.“桃花灼灼有光辉，无数成蹊点更飞”（[唐]苏颋《侍宴桃花园咏桃花应制》）；

57.“源水丛花无数开，丹跗红萼间青梅”（[唐]徐彦伯《侍宴桃花园》）；

58.“林间艳色骄天马，苑里秾华伴丽人”（[唐]张说《桃花园马上应制》；

59.“上阳柳色唤春归，临渭桃花拂水飞”（[唐]张说《奉和圣制初入秦川路寒食应制》）；

60.“芳春桃李时，京都物华好”（[唐]崔湜《饯唐州高使君赴任》）；

61. “香萼媚红滋，垂条萦绿丝”（[唐]徐彦伯《饯唐州高使君赴任》）；

62. “宫梅间雪祥光遍，城柳含烟淑气浓”（[唐]阎朝隐《奉和圣制春日幸望春宫应制》）；

63.“轻丝半拂朱门柳，细缬全披画阁梅”（[唐]李适《奉和春日幸望春宫应制》）；

64.“光风摇动兰英紫，淑气依迟柳色青”（[唐]崔日用《奉和圣制春日幸望春宫应制》）；

65.“晴风丽日满芳洲，柳色春筵祓锦流”（[唐]徐彦伯《上巳日祓禊渭滨应制》）；

66.“宝马香车清渭滨，红桃碧柳禊堂春”（[唐]沈佺期《上巳日祓禊渭滨应制》）；

67.“向浦回舟萍已绿，分林蔽殿槿初红”（[唐]沈佺期《兴庆池侍宴应制》）；

68.“美人含遥霭，桃李芳自薰”（[唐]徐彦伯《题东山子李适碑阴二首》）；

69.“独有归闲意，春庭伴落梅”（[唐]苏颋《和黄门舅十五夜作》）；

70.“何当桂枝擢，还及柳条新”（[唐]张子容《长安早春》）；

71.“暮春三月日重三，春水桃花满禊潭”（[唐]张说《三月三日定昆池奉和萧令得潭字韵》）；

72.“酒筵嫌落絮，舞袖怯春风”（[唐]王维《三月三日勤政楼侍宴应制》）；

73.“杨花雪落覆白苹，青鸟飞去衔红巾”（[唐]杜甫《丽人行》）；

74.“安得健步移远梅，乱插繁花向晴昊”（[唐]杜甫《苏端薛复筵简薛华醉歌》）；

75.“千条嫩柳枝条垂拂青琐，百啭黄莺鸣叫声绕建章”（[唐]贾至《早朝大明宫呈两省僚友》）；

76.“五夜漏声催晓箭，九重春色醉仙桃”（[唐]杜甫《奉和贾至舍人早朝大明宫》）；

77.“桃花细逐杨花落，黄鸟时兼白鸟飞”（[唐]杜甫《曲江对酒》）；

78.“梨花度寒食，客子未春衣”（[唐]钱起《下第题长安客舍》）；

79.“步屧随春风，村村自花柳”（[唐]杜甫《遭田父泥饮美严中丞》）；

80.“春城无处不飞花，寒食东风御柳斜”（[唐]韩翃《寒食》）；

81.“仲月风景暖，禁城花柳新”（[唐]李亨《中和节赐百官燕集因示所怀》）；

82.“杨柳先飞絮，梧桐续放花”（[唐]元稹《咏廿四气诗 清明三月节》）；

83.“深竹与清泉，家家桃李鲜”（[唐]权德舆《奉和崔阁老清明日候许阁老交直之际辱裴阁老书招云与考功苗曹长先城南游览独行口号因以简赠》）；

84.“助君行春令，开花应清明”（[唐]白居易《答桐花》）；

85.“怅望慈恩三月尽，紫桐花落鸟关关”（[唐]白居易《酬元员外三月三十日慈恩寺相忆见寄》）；

86.“故人千万里，新蝉两三声”（[唐]白居易《立秋日曲江忆元九》）；

87.“数日非关王事系，牡丹花尽始归来”（[唐]白居易《醉中归周至》）；

88.“九月降霜秋早寒，禾穗未熟皆青乾”（[唐]白居易《杜陵叟》）；

89.“画栏桂树悬秋香，三十六宫土花碧”（[唐]李贺《金铜仙人辞汉歌》）；

90.“杨花榆荚无才思，惟解漫天作雪飞”（[唐]韩愈《晚春》）；

91.“遮莫杏园胜别处，亦须归看傍村花”（[唐]王建《寒食忆归》）；

92.“中庭地白树栖鸦，冷露无声湿桂花”（[唐]王建《十五夜望月》）；

93.“鸥鸟似能齐物理，杏花疑欲伴人愁”（[唐]罗隐《清明日曲江怀友》）；