Temperature sensitivity of plant phenology in temperate and subtropical regions of China from 1850 to 2009

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ABSTRACT: Phenology can be used to track plant responses to climate change. In China, several studies have found the earlier trends of spring phenophases over the past 50 years. However, few studies put these phenological changes into historical perspective. Based on specific phenophases records from historical diaries and Chinese Phenological Observation Network, we developed spring phenology index (SPI) time series in temperate and subtropical regions of eastern China from 1850 to 2009. We firstly compare the temporal change of SPI and seasonal temperature anomaly. Subsequently, we search for common shifts in phenological and temperature time series by applying the moving *t*-test method, and discuss temperature sensitivity of SPI by using the moving linear regression method for both regions. Results show that the SPI in temperate region revealed lower interannual variability than in subtropical region, while the seasonal temperature variability was higher in temperate region. In temperate region, the timing of significant shift towards earlier SPI (in 1979) coincides with the timing of shift in spring temperature time series. The temperature sensitivities of SPI differ among the two regions. The mean sensitivity of SPI to spring temperature in subtropical region (-3.7 days $^{\circ}\text{C}^{-1}$) is stronger than in temperate region (-2.5 days $^{\circ}\text{C}^{-1}$). The temperature sensitivity of SPI varies among consecutive 30-year periods. In recent three decades, temperature sensitivity of spring phenophases became stronger in both regions.

KEY WORDS plant phenology; spring phenology index; temperature sensitivity; climate change; historical observation

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1. Introduction

Recent climate warming has substantially affected the properties of terrestrial biological systems, such as changing morphology, reproduction or genetics and shifting distribution range of plants (Walther *et al.*, 2002; Rosenzweig *et al.*, 2007). Besides, the change in spring plant phenological events (e.g. leaf unfolding or flowering time) has been detected all over the world (Sparks and Menzel, 2002; Menzel *et al.*, 2006a, 2006b), suggesting that the plant phenophase is an independent and sensitive indicator of climate change (Parmesan and Yohe, 2003; Root *et al.*, 2003). The earlier trends of springtime phenological events observed from the ground corresponded well with the earlier carbon sequestration period obtained from eddy–covariance flux tower (Richardson *et al.*, 2010) and earlier spring green-up onset date documented by satellite at a regional scale (Cong *et al.*, 2013; Wu and Liu, 2013). However, delays of satellite-derived vegetation green-up onset date based on different start of spring methods are also found in some high-latitude regions (White *et al.*, 2009).

As the modern phenological observation usually began after 1950s, most of the recently published studies on plant

phenology focussed on the past half century (Menzel and Fabian, 1999; Zheng *et al.*, 2002; Matsumoto *et al.*, 2003; Doi and Katano, 2008; Doi and Takahashi, 2008; Dai *et al.*, 2013). Very few studies use longer and continuous observation data. However, some unique long-term phenological observations exist. For example, the Marsham family recorded the 27 phenological events for over 20 plants and animals from 1736 in the UK (Sparks and Carey, 1995). In Japan, the cherry blossom dates from Medieval period has been extracted from historical documents and applied to reconstruct springtime temperatures since the 9th century (Aono and Kazui, 2008; Aono and Saito, 2010). The grape harvest dates in historical European documents has been used to reconstruct the summer temperature in Central Europe (Chuine *et al.*, 2004; Meier *et al.*, 2007). Besides, other studies combined the historical phenological observations and reconstructed long-term time series in the UK and Switzerland (Rutishauser *et al.*, 2007; Amano *et al.*, 2010). These long-term datasets have big potential to study the past climate–vegetation relationship and monitor the impact of climate change.

In China, several studies showed 150-year phenological change in Beijing (Gong *et al.*, 1984) and middle and lower reaches of Yangtze River (Zheng *et al.*, 2013) using the phenological records in historical documents and Chinese Phenological Observation Network (CPON). However, these studies used only a limited number of datasets for small regions. In order to acquire more substantial evidence about past phenological change, more

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fragmentary phenological observations in CPON need to be used appropriately. Moreover, the regional differences in phenological change and its associated temperature sensitivity need to be examined, since China covers a broad geographical area.

In this study, we firstly define the spring phenology index (SPI) based on specific plant phenophases and then develop SPI time series in temperate and subtropical regions of eastern China from 1850 to 2009 using the phenological records derived from historical diaries and modern observation network. Subsequently, we describe plant phenology in comparison with seasonal temperature changes and detect the occurrence of common shifts in phenological and temperature time series. Finally, we compare the temperature sensitivity of spring phenology during the study period in the two regions.

2. Data and methods

2.1. Data source

The study area covers eastern China. According to the climatic regionalization of China (Zheng *et al.*, 2010), we divided the study area into two regions: temperate region and subtropical region (Figure 1). Mean annual temperature ranges from -4 to 14°C in the temperate region and from 14 to 22°C in the subtropical region.

Total annual precipitation is between 1000 and 2000 mm in subtropical region. In temperate region, the total annual precipitation decreases from 1000 mm in the southeast to 200 mm in the northwest.

The phenological data in the modern period of the study (1963–2009) are from the CPON, which is administrated through the sponsorship of the Chinese Academy of Sciences (CAS). CPON gathered the phenological data under uniform guidelines (Wan and Liu, 1979). Totally 17 766 observations are available at 56 sites in temperate region and 25 sites in subtropical region (Figure 1).

For the historical period covered by this study (1850–1962), a total of 600 phenological observations were extracted from 20 diaries. A total of 282 observations were acquired from previous studies (Gong *et al.*, 1984; Fang *et al.*, 2005; Zheng *et al.*, 2013), while additional 318 observations were extracted by Ge *et al.* (2014). Although such historical observations were not strictly gathered according to modern criterion and guidelines, many studies have concluded that these phenological observations were often personally motivated and contained reliable information (Zhu, 1973; Rutishauser *et al.*, 2007; Aono and Kazui, 2008), and could be used as a past climate indicator.

In data from both the historical diaries and CPON, 19 species of deciduous woody plants and 9 phases (e.g.

Figure 1. Locations of phenological observation sites: Chinese Phenological observation Network (CPON, 1963–2009) and historical documents. The line near the latitude 33°N shows the boundary between temperate region (TR) and subtropical region (SR).

first flowering, 50% of full flowering, end of flowering, etc.) were analysed (Table 1). The total analysis, therefore, amounted to 57 spring phenophases (one phenophase represents a single phase of a specific species). These phenophases distributed at 100 sites across eastern China are shown in Figure 1.

With regard to the temperature data, we chose the CRUTEM4 dataset, which provides a highly reliable global grid-box dataset of 5° latitude × 5° longitude temperature anomalies (Jones *et al.*, 2012; Morice *et al.*, 2012). After averaging the temperature from the CRUTEM4 on grids representing temperate and subtropical regions, monthly mean temperature anomalies in each region from 1850 to 2009 were obtained. The spring (March–May), winter (December–February), autumn (September–November) and summer (June–August) temperature anomalies are the means of the corresponding monthly data.

2.2. Reconstruction of SPI

2.2.1. Regional aggregation of phenophases

Several fragmentary phenological observations (discontinuous time series) are available at 81 sites of CPON. In order to fill in the gap for single-site observation time series and reduce the weight of exceptionally early or late observation, we combined the observations for each phenophase (species/phase) at all sites within each region (temperate or subtropical region) to form a regional time series from 1963 to 2009. Following Häkkinen *et al.* (1995) and Schaber and Badeck (2002), the combined time series y_i ($i = 1$,

2, ..., M , M is the total number of the years considered) was defined as:

$$y_i = \frac{1}{n_i} \sum_{j=1}^{n_i} (x_{ij} - b_j) \quad (1)$$

where y_i is regional averages of the observations x_{ij} of year i at station j , adjusted by b_j . The variable b_j is the site effect, which is mainly determined by geographic factors (i.e. latitude, longitude and altitude). n_i is the number of observations, and N is the total number of stations considered. $n_i \leq N$ because some x_{ij} are undefined due to the problem that no observations were carried out in year i at station j . The value of b_j is found by an iterative optimization algorithm that minimizes the sum of squared residuals (S):

$$S = \sum_i \sum_j [(x_{ij} - b_j) - y_i]^2 \quad (2)$$

The minimum of S is found by differentiating S with respect to b_j and y_i and setting the resulting derivatives equal to zero. Meanwhile, we could impose $\sum_{j=1}^N b_j = 0$ to obtain a unique solution of b_i and y_i (see Schaber and Badeck (2002) for more details).

2.2.2. Definition of SPI

In the second step, the SPI can be defined as:

$$\text{SPI} = \frac{1}{n} \sum_{l=1}^n y_l \quad (3)$$

where y_l is the combined time series (1963–2009) of a specific phenophase l (Rutishauser *et al.*, 2007; Ge *et al.*, 2014). Following best data availability, we chose three phenophases covering the largest number of years during the modern period (1963–2009) for both regions to define SPI. The three phenophases are first leaf of *Salix babylonica* (weeping willow), and first flowering of *Cercis chinensis* (Chinese redbud) and *Wisteria sinensis* (Chinese wisteria). Consequently, the SPI in each region from 1963–2009 can be obtained by using Equation (3).

2.2.3. Calibration of transfer functions

This step is to calibrate transfer functions between the combined time series of respective phenophase and the 1963–2009 SPI time series for each region (Rutishauser *et al.*, 2007). The transfer functions can be applied to reconstruct historical SPI using the limited data during the historical time period. The transfer function was a linear regression function with parameters d and e :

$$\text{SPI} = d_l y_l + e_l \quad (4)$$

For uncertainty estimates, we cross-validated each phenophase-specific transfer function in the period 1963–2009 (Michaelsen, 1987). Each year was withheld once from the dataset and the transfer function was performed with the retained years, e.g. when the data in 1963 was withheld, the transfer function was calibrated with

Table 1. Summary of species and corresponding phases both recorded in historical documents (1850–1962) and modern observation network (1963–2009).

Species	Phase
<i>Amygdalus persica</i> f. duplex Rehd.	FF, 50F
<i>Chaenomeles speciosa</i>	FF, 50F, EF
<i>Robinia pseudoacacia</i>	FF, 50F, EF
<i>Pyrus</i> sp. (pear)	FF, 50F, EF
<i>Prunus salicina</i>	FF, 50F, EF
<i>Salix babylonica</i>	BB, FL, 50L, FF, 50F, EF, FD
<i>Prunus mume</i>	FF, 50F, EF
<i>Paeonia suffruticosa</i>	FF, 50F, EF
<i>Cerasus yedoensis</i>	FF, 50F, EF
<i>Amygdalus davidiana</i>	FF, 50F, EF
<i>Amygdalus persica</i>	FF, 50F, EF
<i>Malus micromalus</i>	FF, 50F, EF
<i>Armeniaca vulgaris</i>	FF, 50F, EF
<i>Cerasus pseudocerasus</i>	FF, 50F
<i>Ulmus pumila</i>	FM
<i>Magnolia denudata</i>	FF, 50F, EF
<i>Syringa oblata</i>	FF, 50F, EF
<i>Cercis chinensis</i>	FF, 50F, EF
<i>Wisteria sinensis</i>	FF, 50F, EF

Phases: FF, First flowering; 50F, 50% of full flowering; EF, end of flowering; FL, first leaf; 50L, 50 % of full leaf expansion; BB, bud burst; FM, fruit maturity; FD, fruit drop.

the data during 1964–2009. Then we simulated SPI in 1963 using the calibrated transfer function. If the above calculations were repeated for the other years, the simulated interannual SPI could be obtained. We calculated the root mean square error (RMSE) between observed SPI and simulated SPI time series for each phenophase. Uncertainties for the SPI time series can be estimated by using the mean RMSE of all the transfer functions.

2.2.4. Calculation of historical SPI

After completing the above steps, the transfer functions between all the phenophases documented in historical diaries and SPI have been calibrated according to the observations in modern period. Subsequently, for the historical period (1850–1962), we firstly applied Equation (1) to each observation record of specific phenophase to remove the site effect b_j . If phenophase in history was also recorded in the modern period (1963–2009) at the site j , b_j can be known through the process of combining phenological time series (Section 2.2.1). Otherwise, b_j can be estimated by a multiple regression equation between b_j and geographic factors (i.e. latitude, longitude and altitude). Second, we applied the corresponding transfer function (Equation (4)) to reconstruct the SPI. As a result, annual SPI time series in historical period for each region could be obtained by averaging all reconstructed SPI in the same year.

2.3. Statistical Analysis

We applied a 10-year moving average method to investigate decadal change of phenological and temperature anomaly time series. Subsequently, we look for years with shifts in the phenological and temperature time series by applying moving t -test method (Yan *et al.*, 1992). The moving t -test method could detect significant difference between two consecutive periods with same length of time. For each time series (TS), we extracted two subseries x_1 and x_2 in each year i

$$x_1 = [\text{TS}_{i-L}, \text{TS}_{i-(L-1)}, \dots, \text{TS}_{i-1}] \quad (5)$$

$$x_2 = [\text{TS}_{i+1}, \text{TS}_{i+2}, \dots, \text{TS}_{i+L}] \quad (6)$$

where $L = 30$ years. The t statistic to test whether the means of two subseries are different can be calculated as follows:

$$t_i = \frac{x_{1\text{mean}} - x_{2\text{mean}}}{\sqrt{\frac{(n_1-1)S_{x1}^2 + (n_2-1)S_{x2}^2}{n_1+n_2-1}}} \sim t(n_1+n_2-2) \quad (7)$$

where $x_{1\text{mean}}$ and $x_{2\text{mean}}$ are the mean of x_1 and x_2 , respectively. S_{x1} and S_{x2} are the standard deviation of two subseries, respectively. n_1 and n_2 (the actual length of subseries) $\leq L$, since there are some missing data in the phenological or temperature time series. $n_1 + n_2 - 2$ is the total number of degrees of freedom which is used in significance testing. If $|t_i| > t_{0.05/2}(n_1 + n_2 - 2)$, the means

of the two subseries are different at 0.05 level of significance.

Finally, the temporal change of temperature sensitivity of plant phenology over time was described by a moving sensitivity approach (Rutishauser *et al.*, 2009). Following Rutishauser *et al.* (2009), for each 30-year period, temperature sensitivity was calculated as the slope of a linear regression model with SPI as the dependant variable and seasonal temperature anomaly as the independent variable.

3. Results

3.1. SPI reconstruction and associated uncertainties

In both regions, there was generally a strong overall coherence among the defined SPI and the individual phenophase (Table 2). In temperate region, all the phenophases investigated were able to explain 4% to 89% of the SPI variance with a mean of 50%; the RMSE values were between 1.69 and 4.92 days, resulting in a mean reconstruction uncertainty of 3.17 days (Table 2). In subtropical region, the R^2 values were between 1% and 85% with a mean of 48%; the RMSE values were between 2.36 and 5.93 days with a mean of 4.00 days (Table 2).

3.2. Phenological and temperature changes

Seasonal temperature anomaly records are shown in Figure 2. The temperature in temperate region had a higher interannual variability (higher standard deviation) than in subtropical region for all seasons (Table 3). Except for the summer temperature in temperate region, all seasons and both regions showed the increasing temperature trends over the period 1850–2009 (Table 3). The recent decade (2000–2009) contained the largest numbers of very warm springs leading to a positive decadal anomaly of 1.49 °C in temperate region and 1.16 °C in subtropical region. The other decades varied between ± 1.34 °C in temperate region and ± 0.89 °C in subtropical region with respect to the 1961–1990 mean. The coolest spring was found in 1908–1917 in temperate region and 1903–1912 in subtropical region. The winter temperature showed a similar distribution of cold and warm decadal anomalies with spring temperature for both regions (Figure 2).

Figure 3 presents the SPI in temperate and subtropical regions from 1850 to 2009. The mean SPI in temperate region (12 April, Day 102) was 16 days later than the mean of the subtropical region (27 March, Day 86; Table 3). The SPI time series in temperate region also had a lower interannual variability (represented by standard deviation) of 5.0 days in comparison to 6.2 days in subtropical region. The SPI time series in temperate region showed a linear trend of -0.30 days decade⁻¹ over the study period, while the linear trend in subtropical region (-0.71 days decade⁻¹) was stronger (Table 3).

At interannual time scale, the SPI time series in temperate region correlated significantly with the time series in subtropical region ($R = 0.49$, $P < 0.001$). At decadal time scales, the correlation is stronger ($R = 0.69$, $P < 0.001$). In addition, significantly negative correlations were

Table 2. The parameters of transfer functions and reconstruction accuracies for individual phenophases for the estimation of the SPI in temperate and subtropical regions of eastern China.

No.	Species	Phases	Temperate region					Subtropical region				
			<i>N</i>	<i>d</i>	<i>e</i>	<i>R</i> ²	RMSE	<i>N</i>	<i>d</i>	<i>e</i>	<i>R</i> ²	RMSE
1	<i>Amygdalus persica</i> f. duplex Rehd.	FF	35	d	e	0.49*	3.22	—	—	—	—	—
2	<i>Amygdalus persica</i> f. duplex Rehd.	50F	30	0.72	28.29	0.45*	3.41	—	—	—	—	—
3	<i>Chaenomeles speciosa</i>	FF	30	0.70	28.13	0.89*	1.69	26	0.52	43.83	0.62*	3.92
4	<i>Chaenomeles speciosa</i>	50F	25	0.65	37.81	0.86*	1.93	26	0.58	35.98	0.70*	3.46
5	<i>Chaenomeles speciosa</i>	EF	24	0.64	34.80	0.11	4.92	26	0.64	21.61	0.42*	4.85
6	<i>Robinia pseudoacacia</i>	FF	47	0.50	41.72	0.46*	3.57	36	0.88	−17.43	0.49*	4.31
7	<i>Robinia pseudoacacia</i>	50F	44	0.84	−5.98	0.54*	3.30	36	0.84	−15.98	0.45*	4.47
8	<i>Robinia pseudoacacia</i>	EF	42	0.91	−18.41	0.30*	4.08	36	0.71	−6.30	0.32*	4.97
9	<i>Pyrus</i> sp.	FF	24	0.86	−18.64	0.19*	3.29	19	0.21	67.36	0.01	4.49
10	<i>Pyrus</i> sp.	50F	22	0.42	56.05	0.09	3.31	19	0.20	67.22	0.01	4.52
11	<i>Pyrus</i> sp.	EF	22	0.35	62.98	0.14	3.94	19	0.37	49.50	0.11	4.15
12	<i>Prunus salicina</i>	FF	35	0.36	57.58	0.36*	3.68	19	0.29	64.33	0.26*	4.03
13	<i>Prunus salicina</i>	50F	35	0.59	32.96	0.11	4.37	19	0.50	46.21	0.46*	3.18
14	<i>Prunus salicina</i>	EF	33	0.43	50.04	0.26*	4.00	18	0.43	47.93	0.49*	3.06
15	<i>Salix babylonica</i>	FL	40	0.54	34.18	0.80*	2.15	41	0.71	36.23	0.67*	3.45
16	<i>Salix babylonica</i>	50L	40	0.78	30.26	0.67*	2.78	41	0.59	38.40	0.56*	4.00
17	<i>Salix babylonica</i>	BB	39	0.83	18.81	0.34*	3.97	40	0.60	47.52	0.39*	4.78
18	<i>Salix babylonica</i>	FF	39	0.43	67.02	0.62*	3.01	41	0.82	21.12	0.69*	3.34
19	<i>Salix babylonica</i>	50F	40	0.85	16.96	0.47*	3.55	41	0.94	6.28	0.78*	2.84
20	<i>Salix babylonica</i>	EF	39	0.68	30.74	0.60*	3.10	41	0.89	4.09	0.72*	3.16
21	<i>Salix babylonica</i>	FD	39	0.75	19.85	0.52*	3.38	33	0.54	23.99	0.40*	4.82
22	<i>Prunus mume</i>	FF	28	0.51	34.68	0.29*	3.82	17	0.31	69.62	0.18	4.99
23	<i>Prunus mume</i>	50F	28	0.26	79.39	0.04	4.49	17	0.38	61.96	0.30*	4.60
24	<i>Prunus mume</i>	EF	28	0.06	93.50	0.06	4.49	17	0.43	51.87	0.33*	4.50
25	<i>Paeonia suffruticosa</i>	FF	44	0.07	92.14	0.71*	2.64	15	0.79	7.16	0.41*	3.66
26	<i>Paeonia suffruticosa</i>	50F	47	0.89	−3.71	0.72*	2.57	15	0.88	−6.77	0.31*	3.98
27	<i>Paeonia suffruticosa</i>	EF	41	1.00	−19.61	0.46*	3.59	14	0.62	15.68	0.20	4.24
28	<i>Cerasus yedoensis</i>	FF	43	0.71	8.04	0.75*	2.31	26	0.54	34.44	0.71*	3.43
29	<i>Cerasus yedoensis</i>	50F	41	0.63	32.21	0.58*	3.00	26	0.63	24.37	0.69*	3.54
30	<i>Cerasus yedoensis</i>	EF	39	0.66	25.95	0.45*	3.44	26	0.66	14.31	0.51*	4.44
31	<i>Amygdalus davidiana</i>	FF	47	0.51	37.34	0.46*	3.60	—	—	—	—	—
32	<i>Amygdalus davidiana</i>	50F	46	0.73	35.57	0.49*	3.49	—	—	—	—	—
33	<i>Amygdalus davidiana</i>	EF	42	0.80	26.68	0.52*	3.20	—	—	—	—	—
34	<i>Amygdalus persica</i>	FF	34	0.80	18.43	0.60*	2.28	37	0.74	26.80	0.68*	3.39
35	<i>Amygdalus persica</i>	50F	34	0.67	33.70	0.58*	2.34	37	0.81	15.83	0.62*	3.73
36	<i>Amygdalus persica</i>	EF	33	0.72	26.42	0.31*	3.00	37	0.92	−0.27	0.64*	3.60
37	<i>Malus micromalus</i>	FF	43	0.65	28.79	0.70*	2.55	—	0.00	0.00	—	—
38	<i>Malus micromalus</i>	50F	42	0.89	5.02	0.72*	2.44	—	0.00	0.00	—	—
39	<i>Malus micromalus</i>	EF	41	0.87	4.01	0.54*	3.12	—	0.00	0.00	—	—
40	<i>Armeniaca vulgaris</i>	FF	45	0.79	7.11	0.76*	2.39	26	0.49	49.99	0.43*	4.83
41	<i>Armeniaca vulgaris</i>	50F	43	0.98	7.09	0.74*	2.46	26	0.49	48.79	0.47*	4.64
42	<i>Armeniaca vulgaris</i>	EF	42	0.95	6.54	0.60*	3.08	26	0.64	32.32	0.58*	4.14
43	<i>Cerasus pseudocerasus</i>	FF	22	0.95	0.44	0.38*	2.46	—	—	—	—	—
44	<i>Cerasus pseudocerasus</i>	50F	22	0.53	40.94	0.39*	2.46	—	—	—	—	—
45	<i>Ulmus pumila</i>	FM	39	0.57	34.98	0.62*	2.99	32	0.43	38.02	0.15*	5.93
46	<i>Magnolia denudata</i>	FF	44	1.10	−34.10	0.60*	2.92	34	0.57	42.87	0.34*	5.03
47	<i>Magnolia denudata</i>	50F	42	0.51	54.76	0.69*	2.57	34	0.74	26.27	0.55*	4.13
48	<i>Magnolia denudata</i>	EF	41	0.60	44.55	0.47*	3.36	34	0.74	19.00	0.62*	3.79
49	<i>Syringa oblata</i>	FF	46	0.62	37.67	0.49*	3.49	22	0.61	27.61	0.67*	3.23
50	<i>Syringa oblata</i>	50F	44	0.81	9.49	0.42*	3.71	22	0.71	14.54	0.57*	3.69
51	<i>Syringa oblata</i>	EF	41	0.80	6.03	0.34*	3.95	15	0.33	49.27	0.10	4.35
52	<i>Cercis chinensis</i>	FF	47	0.87	−11.01	0.79*	2.23	37	0.77	17.71	0.82*	2.58
53	<i>Cercis chinensis</i>	50F	45	0.81	20.32	0.78*	2.26	37	0.83	6.50	0.85*	2.36
54	<i>Cercis chinensis</i>	EF	42	0.76	21.43	0.47*	3.57	36	0.71	8.03	0.48*	4.38
55	<i>Wisteria sinensis</i>	FF	44	0.65	25.40	0.71*	2.64	36	0.80	3.07	0.70*	3.26
56	<i>Wisteria sinensis</i>	50F	44	0.78	12.03	0.61*	3.03	36	0.83	−3.91	0.67*	3.43
57	<i>Wisteria sinensis</i>	EF	42	0.79	7.89	0.23*	4.30	36	0.75	−3.55	0.48*	4.32

See Table 1 for phases description. *N*: Number of years with observation data between 1963 and 2009; *d*, *e*: parameters of transfer functions (Equation (4)); RMSE: root mean square error of cross-validated SPI reconstruction; *R*²: variance of SPI explained by respective single phenophase. **P* < 0.05.

Figure 2. The seasonal mean temperature anomalies (with respect to 1961–1990 mean) in temperate and subtropical regions of eastern China for the period 1850–2009. Spring temperatures are of the current year, while the temperatures in other seasons are of the previous year. The bold lines show the time series of 10-year moving average.

found between the indices and temperature anomaly in spring and preceding winter for both regions (Table 4), suggesting the warmer winter and spring lead to an earlier plant phenophase. Compared to spring and preceding winter temperature, the preceding autumn and summer temperatures have weaker correlations with the SPI, although the correlation coefficients were still statistically significant in subtropical region (Table 4).

3.3. Shifts in phenological and temperature time series

Phenological and temperature time series were analysed by moving *t*-test method for shifts. Two statistically significant shifts towards earlier spring phenophases were found in SPI time series for temperate region (Figure 4). The timing of the first shift was 1917. The timing of the second shift was 1979, suggesting the spring phenophases in 1980–2009 were significantly earlier than the preceding 30 years. For subtropical region, the SPI showed significant shift towards earlier plant phenophases in 1901 and 1937 and towards later plant phenophases in 1970 and 1975.

Two statistically significant shifts towards a warmer temperature could be found in both spring temperature anomaly time series (Figure 4). The timings of the shifts were 1938 and 1979 for temperate region and 1919 and

1979 for subtropical region. For winter temperature, the timings of the shifts were 1978 for temperate region and 1902 and 1978 for subtropical region. For autumn temperature, shifts towards colder temperature were most probable in 1956 while shifts towards warmer temperature were most probable in 1978 for both regions. Regarding summer temperature, shifts towards colder temperature were most probable in 1884 and 1955 for temperate region and in 1881 for subtropical region, while shifts towards warmer temperature were in 1924 and 1979 (temperate region) and in 1922 and 1978 (subtropical region).

3.4. Temperature sensitivity of SPI

The temperature sensitivity is represented by slope of regression between the SPI and temperature time series for each 30-year window. The responses to a 1 °C increase in spring temperature during a 30-year moving window were -0.9 to -4.6 days in temperate region and -0.1 to -6.7 days in subtropical region (Figure 5). Furthermore, the mean sensitivity of SPI on spring temperature (-3.7 days °C $^{-1}$) in subtropical region is significantly stronger than the mean (-2.5 days °C $^{-1}$) in temperate region (unequal variance *t* test, $P < 0.001$), although the uncertainties are generally higher in subtropical region

Table 3. Summary of phenological and temperature anomalies (relative to 1961–1990 mean) time series (from 1850 to 2009) in temperate region (TR) and subtropical region (SR) of eastern China

	Mean	SD	Linear trend
Spring phenology index			
TR	102	5.0	−0.30
SR	86	6.2	−0.71
Temperature anomaly			
TR			
Spring	−0.22	1.06	0.098
Winter	−0.17	1.38	0.124
Autumn	0.18	0.78	0.036
Summer	0.33	0.66	−0.012
SR			
Spring	−0.11	0.75	0.077
Winter	0.07	0.93	0.062
Autumn	−0.07	0.66	0.059
Summer	−0.11	0.54	0.036

Spring: March–May; winter: December–February; autumn: September–November; summer: June–August. Units for 'Mean' and 'SD' column–SPI: days; temperature: °C. Units for 'Linear trend' column–SPI: days decade^{−1}; temperature: °C decade^{−1}.

Figure 3. Spring phenology index (SPI) time series for (a) temperate and (b) subtropical regions of eastern China in the period 1850–2009. The bold lines show the time series of 10-year moving average. The dashed lines show the 1961–1990 means. The shaded areas show the reconstruction uncertainties (2-RMSE).

than in temperate region. The response to winter temperature was -0.1 to -2.2 days °C^{−1} and 0 to -5.5 days °C^{−1} in temperate region and subtropical region, respectively. Similarly, the mean sensitivity of SPI on winter temperature (-2.5 days °C^{−1}) in subtropical region is significantly stronger than the mean (-1.1 days °C^{−1}) in temperate region (unequal variance *t*-test, $P < 0.001$). Therefore, mean temperature sensitivity was systematically different for both regions and all seasons (Figure 5). In addition, the temperature sensitivities were unstable over time. For both regions, the temperature sensitivity of SPI gradually became stronger after 1975 (Figure 5).

Table 4. The Pearson *R* between spring phenology index (SPI) and mean temperature anomalies of spring and preceding winter, autumn and summer in the period 1850–2009.

	Spring	Winter	Autumn	Summer
TR	−0.60*	−0.42*	−0.13	−0.05
SR	−0.64*	−0.56*	−0.37*	−0.28*

TR: temperate region. SR: subtropical region. Spring: March–May; winter: December–February; Autumn: September–November; Summer: June–August. * $P < 0.05$.

4. Discussion

Through correlation analysis, we found the spring temperature impacts plant phenology significantly in both regions (Table 4). This result is in accordance with the previous studies on spring phenology in other countries (Matsumoto *et al.*, 2003; Wolfe *et al.*, 2005; Menzel *et al.*, 2006a, 2006b). Winter temperature of the previous year is also assigned statistical influence on spring phenophases of the current year in both regions. In addition, the impact of autumn and summer temperature is significant in subtropical region (Table 4). The impacts of the previous winter and summer temperature were also found in Japan, where the warmer winter temperature and previous mid-July temperature accelerated the flowering of *Prunus* spp. significantly (Doi, 2007; Doi *et al.*, 2008). Other studies indicated that a warmer winter could reduce the chilling fulfilment of some species and then lead to later spring phenophases (Körner and Basler, 2010; Wilczek *et al.*, 2010). However, our study did not support this conclusion. The possible reason is that most of the species we investigated (e.g. *C. chinensis* and *W. sinensis*) are native to warm regions, so their spring development is primarily controlled by warm temperature rather than chilling temperature (Körner and Basler, 2010). Another reason may be that the chill accumulation has already finished before the early winter. For example, chill accumulation phase of chestnut tree in Beijing is from late October to early January (Guo *et al.*, 2013), therefore, the following warmer late winter and spring temperature leads to earlier spring phenophases.

Long-term temperature and phenological time series potentially experiences more than one shift. Therefore, we used the moving *t*-test technique for break point detection (Figure 4). In temperate region, the spring, autumn and summer temperatures have two shifts (1915–1940, 1979) towards warmer temperature, while temperature time series of winter experiences only one shift in 1978. In subtropical region, seasonal temperatures have experienced two shifts towards warmer temperature: the first one is between 1900s and 1920s; the second one is in 1978 or 1979. Previous study found that there is a broad maximum warmer anomalies from the 1920s to 1940s, a cool trend between 1950s and early 1980s, and another temperature rise from the middle 1980s in China (Wang and Gong, 2000), which was consistent with the timing of shifts detected in this study. To date, there is no study

Figure 4. Moving *t*-test curves with subseries length of 30 years for spring phenology index (SPI) and seasonal temperatures (*T*) time series. The plotted lines show the test statistic (see Section 2.3) for each year. Dashed lines indicate the 95% confidence interval.

Figure 5. Moving temperature sensitivity between spring phenology index (SPI) and spring (March–May) and winter (December–February) temperature in temperate and subtropical regions of eastern China. Sensitivities are the regression coefficients in each 30-year window. The period with more than 10 years missing data are not shown. The shaded areas indicate the 95% confidence interval.

concerning the occurrence of common shifts in phenological and temperature time series in China. Here, we found the common shift in spring phenophases and temperature time series for temperate region, further supporting the conclusion that the recent climate change has impacted the plant life cycle definitely. However, in subtropical region, no significant shift towards earlier spring is detected in phenological time series in past 60 years. The possible reason is the data gap between 1951 and 1962 (Figure 3).

The interannual variability of spring phenophases over the entire 1850–2009 period in subtropical region was higher than in temperate region. However, the seasonal mean temperature revealed a greater variability in temperate region (Table 3). This contradiction can be explained by the stronger temperature sensitivity of spring phenophases in subtropical region (Figure 5). The regional difference of temperature sensitivity found in this study is also documented by Dai *et al.* (2013) and Doi and Takahashi (2008),

who found the leaf unfolding time and leaf colouring time of several woody plants are more sensitive in lower latitude. Similarly, in Europe, most of the spring phenophases exhibited a stronger response to temperature in warmer than in colder countries (Menzel *et al.*, 2006a, 2006b). The possible reason is that the additional heat accumulation available for promoting the flowering or leaf unfolding in lower latitude would be significantly greater than in higher latitude if the temperature increased by the same amount (Dai *et al.* 2013). This is due to the longer duration of heat accumulation in lower latitude than in high latitude.

Changes in temperature sensitivity are much more variable when calculated from spring temperature rather than winter temperature (Figure 5). In temperate and subtropical region, the temperature sensitivity of the SPI was respectively up to $-4.6 \text{ days } ^\circ\text{C}^{-1}$ and $-6.2 \text{ days } ^\circ\text{C}^{-1}$ during the past 30 years, which exceeds all previously temperature sensitivity in other 30-year periods. The changing temperature sensitivity with different time period is also found by other studies. For example, the flowering time of woody plants in Beijing is more responsive in 1990–2007 than in 1963–1989 (Bai *et al.*, 2011). Another study showed that the temperature sensitivity of Swiss plant phenology to spring temperatures has changed within the last three centuries (Rutishauser *et al.*, 2008). These results suggested that the temperature sensitivity of spring phenophase varies with time periods and regions. Therefore, when using the historical phenological records to infer the temperature change, the problem of spatio-temporal difference in temperature sensitivity should be addressed.

5. Conclusions

This study compared phenological and seasonal temperature anomaly time series in temperate and subtropical regions of eastern China from 1850 to 2009. The SPI in temperate region shows lower interannual variability than in subtropical region, in contradiction to higher seasonal temperature variability in temperate region. When a moving window linear regression approach was applied, we found that the temperature sensitivity of spring phenophases became stronger in the past three decades. Moreover, the temperature sensitivity in subtropical region is stronger than in temperate region. In temperate region, the SPI in recent 30 years is significantly earlier than the previous 30 years, which coincides with the significant shift in 1979 in spring temperature time series. Overall, increasing temperatures in recent decades impact the spring plant phenophases in China significantly.

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