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ScienceDirect
Agricultural and Forest Meteorology 138 (2006) 120–131
AGRICULTURAL AND FOREST METEOROLOGY
www.elsevier.com/locate/agrformet

Advance of tree-flowering dates in response to urban climate change

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Received 4 November 2004; received in revised form 24 March 2006; accepted 12 April 2006

Abstract

An increase in temperature due to greenhouse effects is manifest in the changes in diurnal, annual and inter-annual patterns, which may alter phenological events in plants. Flowering dates of four tree species, *Prunus davidina*, *Prunus armeniaca*, *Robinia pseudoacacia* and *Syringa oblata*, were significantly advanced in response to temperature increase over the years 1950–2004 in Beijing, China, due to the impact of urban climate warming. Because both climate warming and the urban heat island effect in winter and early-spring were more rapid than in late-spring and early summer, the dates in early flowering species advanced more quickly than in late flowering species. The early flowering species, *P. davidina*, advanced by 2.9 days/decade, while the other species advanced by 1.5–2.0 days/decade during 1950–2004. Therefore, the intervals between flowering dates of different species were expanded. *P. davidina*, flowering in early-spring, was much more sensitive to minimum and average temperatures (2.88–2.96 days/°C), but less sensitive to maximum temperature (2.46 days/°C). *R. pseudoacacia*, flowering late in the warmer season, was more sensitive to average and maximum temperatures (2.45–2.89 days/°C), but less sensitive to minimum temperature (1.91 days/°C). Statistical analysis showed that, in Beijing, plant flowering is most sensitive to average temperature over 30 days before average blossom date. On the basis of the temperature response curve, the goodness of fitting demonstrates that spring flowering dates can be predicted from the period when temperature is over 0 °C.

Keywords: Tree phenology; Flowering date; Climate warming; Temperature; Urban heat island; Beijing

1. Introduction

Because phenological rhythms are closely related to climate, there is increased analysis of the variations in phenological phases and growth lengths in the context of climate change (Menzel and Fabian, 1999). Many observations on phenological shifting in response to climate change have been reported from different parts of the globe, such as in Europe by Sparks et al. (2000). Phenological phases advanced in spring and were delayed in autumn, while the growth period was extended (Menzel and Fabian, 1999; Walther et al., 2002). Because models of plant productivity consist of submodels of growth, physical and chemical processes in soil and plant phenology, which are affected by meteorological factors, changes in phenological phases will influence plant growth, as well as water and carbon cycles within the ecosystem (Van Wijk et al., 2003).

As mentioned before, there is an increasing number of studies on plant phenological changes from a wide range of regions with different ecosystems. These changes are

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doi:10.1016/j.agrformet.2006.04.002

sensitive and easily observable indicators of biosphere changes in response to climate warming (Peñuelas and Filella, 2001). Walther et al. (2002), in a review, showed that studies in Europe and North America revealed phenological trends, which very probably reflect responses to recent climate change. Chmielewski and Rötzer (2001) reported that a nearly Europe-wide warming in early-spring over the last 30 years (1969–1998) led to an earlier beginning of the growing season by 8 days. In Europe, for the period 1951–1996, phenological phases in spring, such as leaf unfolding, have advanced 6.3 days (−0.2 day/year), whereas autumn events, such as leaf coloring, have been delayed by 4.5 days (0.15 day/year) (Menzel and Fabian, 1999; Menzel, 2000). The average growing season has lengthened by 10.8 days in Europe since the early 1960s. In western Canada, *Populus tremuloides* showed a 26-day shift to earlier blooming over the last century (Beaubien and Freeland, 2000). In Estonia, springtime has advanced 8 days over the last 80 years, with a faster change in the last 40 years (Ahas et al., 2000). Plant phenophases also advanced in spring and were delayed in autumn in China over the last 40 years (Zhang, 1995; Zheng et al., 2002; Schwartz and Chen, 2002; Lu et al., 2006). In Mediterranean ecosystems, the leaves of most deciduous plant species now unfold, on average, 16 days earlier and fall, on average, 13 days later than they did 50 years ago (Peñuelas et al., 2002). Fitter et al. (1995) reported that warmer spring temperatures advanced flowering dates by ~4 days per degree increase in the mean monthly temperature. In general, for a 3.5 °C increase in temperature, spring flowering will occur about 2 weeks earlier for boreal, temperate and Mediterranean forest ecosystems (Kramer et al., 2000). All these reports contribute to an understanding of the wide-ranging effects of climate warming.

Phenology observations in modern ecological research in China were initiated in the 1930s, but were interrupted during World War II (Wan, 1942). The Phenological Network of China was formed in the early 1960s. Its mission was to establish relationships (if any) between plant and animal phenology and crop growth, and to propose a natural calendar suitable for agricultural activities, because Chinese farmers have been accustomed to obtaining information on seasonal climatic variations from phenological phenomena for thousands of years.

Climate warming is characterized by diurnal, annual and inter-annual variations in temperature. Analysis of global mean surface air temperature has shown that its increase is due to changes in daily maximum and minimum temperatures. Global minimum temperatures are increasing faster than maximum temperatures, resulting in a narrowing of the diurnal temperature range. There are a number of possible factors, such as an increase in cloud cover, contributing to decreases in the diurnal temperature range (Easterling et al., 1997). Urban heat island is another factor influencing climate, which often tends to manifest itself strongest during the nighttime hours. Increase in urbanization may differentially increase the minimum relative to the maximum temperature (Karl et al., 1993). In mid-latitude North American cities the urban–rural temperature difference usually peaks shortly after sunset, then slowly decreases until shortly after sunrise, after which it rapidly decreases. The ecological consequences of this change are largely unexplored. For example, the response of plant phenological phases to these changes in minimum and maximum temperatures remains uncertain, although Alward et al. (1999) reported on the different sensitivities of rangeland plants to increases in minimum temperature.

Beijing (39°56′N, 116°17′E, 54 m above sea level), the capital of China, is located in the North China Plain, which has temperate monsoon climate, with monthly maximum temperatures of 26–30 °C in July and minimum temperature ranging from −5 to 2 °C in January. The temperature increases rapidly from February to May, and spring is very short. As the summer monsoon, starts in the spring, there are much greater variations in temperature, precipitation and solar radiation than at the same latitude in the American and European continents (Domros and Peng, 1988). Therefore, there are marked inter-annual variations of climate in the city, and significant variations of phenology (Lu et al., 2006).

This study attempts to answer the question of how flowering responds to climate warming, i.e. the influence of changes in amplitude of temperature at diurnal, annual and inter-annual scales on the shift of flowering dates. The objectives of this study are: (1) to analyse the sensitivity of flowering dates of four tree species to temperature, based on long-term observations in Beijing, China; (2) to identify significant periods when temperature influences flowering in a temperate monsoon climate; (3) to apply a model, based on thermal sensitivity of plant development, to predict flowering dates.

2. Materials and methods

The Phenological Observation Network of China was initiated in the early 1960s, but was interrupted after 1988, except for Beijing. The methods of phenological observation have been described in detail by Wan and Liu (1979) and Lu et al. (2006). From the beginning, the observation methods were standardized and performed consistently.

2.1. Background of the phenological observation

Observational sites were representative, which avoided special microclimate areas, such as hilly tops, deep valleys or wetlands. Selected trees were robust and middle-aged, at least 3 years after the first blossom, and were used as observation trees consistently during the study period. Phenological observations were perennial work, conducted every day during the growth period. In particular, observations were made in the morning or afternoon when plants regularly bloomed (Wan and Liu, 1979).

For boreal and shrub plants, the observational position was taken on the southern side of the plant. As each development stage may occur at different times for each plant and shoot, beginning and flourishing dates of bloom were determined according to percentages of plant in blossom. One stage will begin when 10% of the plant emerges, while another is labelled as the flourishing stage when 50% of the plant emerges. Leaf flushing dates, beginning of blooming, flourishing of blooming, end of flowering, maturity of fruit or seeds, dropping of fruit or seeds, new shoot growth stage, color change of leaves in autumn and defoliation phase were observed. The records of flowering dates when 50% of plant reaches the stage were analyzed in this study because flowering is regularly observed and reported.

Plant species for observation were selected by considering its dominance in regional distribution and its popularity in ancient times and in other countries, so as to compare historically the same site or different countries at the same time.

2.2. Phenological data

Phenological observations were conducted at Beihai Park and Summer Palace in Beijing, China. Both are former royal gardens, which have a history of more than 150 years. The observed plants were the same in all observation years. Records of phenological phases were taken in Beihai Park from 1950 to 1973 (Zhu and Wan, 1980), and in the Summer Palace from 1963 to 2004. The former is located in the city center, while the latter is in the suburbs.

Four tree species, peach (*Prunus davidina*), almond (*Prunus armeniaca*), acacia (*Robinia pseudoacacia*) and lilac (*Syringa oblata*), were chosen in this study. Besides the 1950–1973 phenological records from Zhu and Wan (1980) for four tree species, other records from 1963 to 1988 have been recorded in annual reports (Institute of Geography, Chinese Academy of Sciences, 1989) when the network existed (Lu et al., 2006). Thereafter, observations in the Summer Palace were continued at the Institute (now Institute of Geographical Sciences and Natural Resources Research, located in Beijing).

Flowering dates were recorded in both Beihai Park and the Summer Palace during 1963–1973. Correlations between flowering dates of both sites (Y for the Summer Palace, and X for the Beihai Park) are as follows:

- $Y = 0.975X + 3.90$ ($R^2 = 0.96^{**}$, RMSE = 1.69 days) for *P. davidina*;
- $Y = 0.925X + 11.54$ ($R^2 = 0.95^{**}$, RMSE = 1.73 days) for *P. armeniaca*;
- $Y = 0.490X + 53.44$ ($R^2 = 0.82^{**}$, RMSE = 1.81 days) for *S. oblata*;
- $Y = 0.995X + 0.746$ ($R^2 = 0.77^{**}$, RMSE = 2.21 days) for *R. pseudoacacia*;

in which ** stands for significance level <0.01. Close relationship was found with root mean-square error (-RMSE) ranging from 1.69 to 2.21 days. The R^2 and RMSE for *S. oblata* demonstrated close relationship between both sites. Its flowering in the Summer Palace may advance 0.49 day with 1 day advance in the Beihai Park in the urban, but the slopes of other three species were near 1. The low ratio suggested different sensitivity of the varieties of *S. oblata* in both sites. We assumed that change in urbanization is not significant before 1973, and the relationship may hold constantly. The flowering dates from 1950 to 1962 in the Summer Palace were retrieved from the Beihai Park, which were shown in (Fig. 2). Therefore, the flowering dates from 1950 to 1962 in the Summer Palace were derived from Beihai Park to obtain a long-term serial phenological record. Trees in the Summer Palace blossomed about 1–3 days later than Beihai Park.

2.3. Climate data

To identify the significant period of temperature determining flowering dates of trees in Beijing, daily maximum, minimum and average temperatures in Beijing during 1950–2004 were used. The data were from the Meteorological Bureau of China. The Beijing Meteorological Station (39°56′N, 116°17′E, 54 m above sea level) is also located in the suburbs; 7.5 km from Beihai Park and 2.5 km from the Summer Palace.

Temperature is the most important factor influencing phenological phases in a temperate monsoon climate. Average temperature and daily maximum and minimum temperatures over a 10-day period were considered as a basic unit. We adopted a method to define climatic factors for different intervals. The temperature influence was assumed to start when daily temperature increased over 0 °C from winter to spring, and to end on the day of blooming. This period was divided into several sub-periods and the average temperature within each sub-period was calculated. Temperature in these sub-periods was considered an independent variable with variable lengths, i.e. 20, 30 or 40 days. A 10-day period was taken as a basic unit; for example, the period from 1 March to 10 April is divided into ten sub-periods of different lengths, i.e. 1–10 March, 11–20 March, 21–31 March, 1–10 April for 10 days (or 11 days), and 1–20 March, 11–31 March, 21 March–10 April for 20 days (or 21 days), and 1–31 March and 11 March–10 April for 30 days (or 31 days), and 1 March–10 April for 40 days (or 41 days).

To determine the significant period of temperature influence on flowering date, regression analysis was applied. Since the period of temperature influence on flowering dates can start when temperature rises above 0 °C, the period during which temperature is above 0 °C in the winter to the day of flowering was covered in the statistical analysis, although it changes annually. Based on the time series of average temperature in each year during 1963–1988, significant periods of temperature influence can be established by linear regression analysis.

The temperature was aggregated and averaged into different factors with variable periods, i.e. 10, 20, 30, 40 and 50 days. Thereafter, significant factors can be established by the regression analysis.

2.4. The model

We assume that days taken to pass through a phenological phase are only dependent on temperature (Robertson, 1968; Angus et al., 1981; Gao et al., 1992). Moreover, we assume that the passage is completed if the developmental rates, integrated over time, are equal to 1, which is called the rate summation method (Baumgärtner et al., 1998).

Development rate is 0 at the two extreme temperatures under which development may stop, and there is an optimum temperature of development, which can be expressed as non-linear model (Gao et al., 1992; Yin et al., 1995):

$$V = a(T - T_{\min})^{1+p}(T_{\max} - T)^{1+q} \tag{1}$$

in which V is development rate, i.e. the reciprocal of development duration (n); T daily average temperature; $T_{\max}$ and $T_{\min}$ the upper and lower limits of temperature for development, respectively; a is a constant.

Parameters a, p and q define the shape of temperature–development response curve. The plant starts to develop when temperature increases from the minimum, and reaches its maximum development rate under optimum temperature. Then, the development is inhibited increasingly with an increase in temperature, and reaches zero at the maximum temperature.

The accumulated development rate from start of growth to flowering is 1:

$$\sum_{i=1}^{n} V(i) = 1 \tag{2}$$

This integration is from the beginning of growth, and n is the number of days from the beginning of development to flowering. Development may start when average temperature is higher than $T_{\min}$. The following relationship holds upon integration of Eq. (1) over the period:

$$a\sum_{i=1}^{n}[(T_i - T_{\min})^{1+p}(T_{\max} - T_i)^{1+q}] = 1 \tag{3}$$

The values of parameters, a, p and q, were obtained by regression. Previously, the values were provided and items in the model were integrated day by day until $a\sum_{i=1}^{n}[(T_i - T_{\min})^{1+p}(T_{\max} - T_i)^{1+q}]$ reach 1, signifying the simulated arrival of the flowering date. By adjusting the values of a, p and q, the maximum correlation coefficient between simulated and observed flowering dates can be obtained, which is taken as the best fit.

3. Results

In a monsoon climate, temperature is a dominant factor controlling phenological changes in the spring (Zhang, 1995). The time trend of temperature and flowering dates were analyzed to reveal their relationship.

3.1. Time trend of temperature

Climate warming can be characterized by increases in maximum, minimum and average temperatures. Time trend of monthly maximum, minimum and average temperatures from February to May is shown in Fig. 1. There are significant trends of increasing temperatures over the period from 1950 to 2004: it is

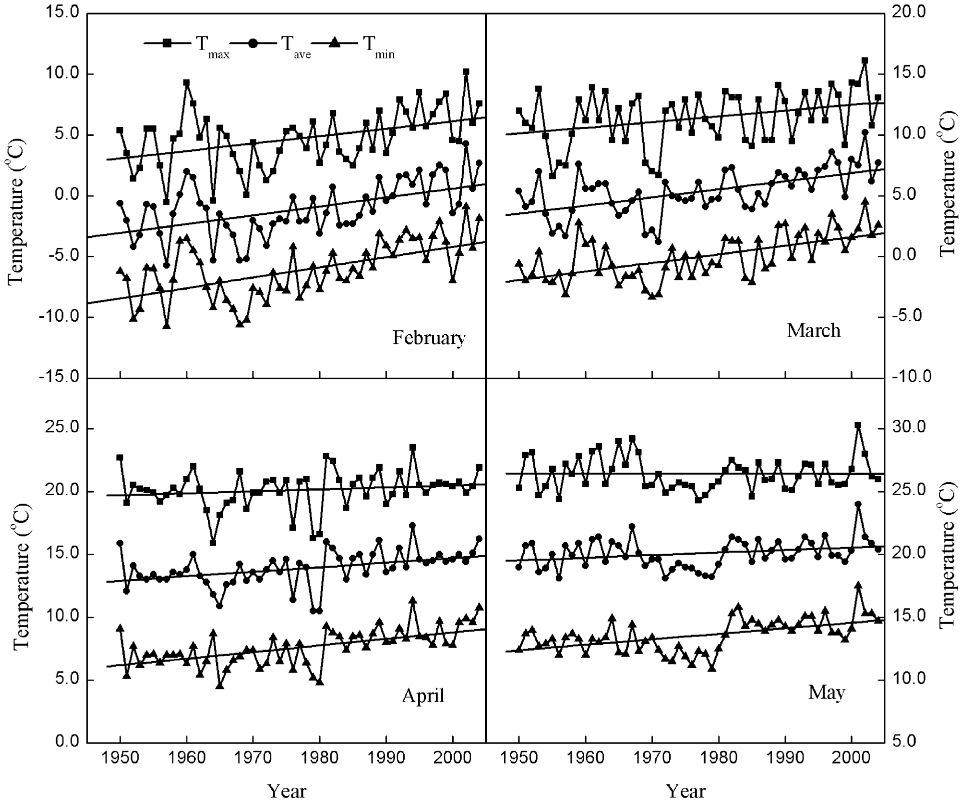

Fig. 1. Time trends of monthly average of daily maximum, minimum and average temperatures in Beijing (7.5 km from Beihai Park and 2.5 km from the Summer Palace, 1950–2004).

most significant in the winter and early-spring. The increase in minimum temperature is greater than that of maximum and average temperatures. The rates of increase of maximum and minimum temperature are in the range 0.0–0.61 and 0.44–0.85 °C/decade, respectively (Table 1). However, daily minimum temperatures have generally increased at a higher rate than the maximum daily temperatures, resulting in a decrease in the diurnal temperature range. It has been revealed that the annual average of maximum temperature increased by 0.127 °C/decade in China during 1955–2000, while the annual average of minimum temperature increased by 0.323 °C/decade (Liu et al., 2004).

Generally, the increase of temperature is higher in February and March than in April and May (Fig. 1). The maximum temperature hardly increased in April and May, whereas the minimum temperature still increased in this period, although the rate of increase was lower than in February and March. The increase in average temperature was also the highest in February, and smallest in May. This indicates that urban climate warming was more significant during cold seasons of the year or cold times in a day. While temperature increased in different seasons, the rate of increase changed with time. This difference may alter the trend of phenological change.

Table 1
The rate of temperature increase from 1950 to 2004 in spring

Month	T_{max} (°C/decade)	P	T_{ave} (°C/decade)	P	T_{min} (°C/decade)	P
February	0.61**	0.0020	0.72**	<0.0001	0.85**	<0.0001
March	0.47*	0.0136	0.67**	<0.0001	0.71**	<0.0001
April	0.16	0.2423	0.36**	0.0017	0.53**	<0.0001
May	0.00	0.9412	0.20*	0.0425	0.44**	<0.0001

* P values is significance level, represents <0.05.
** P values is significance level, represents <0.01.

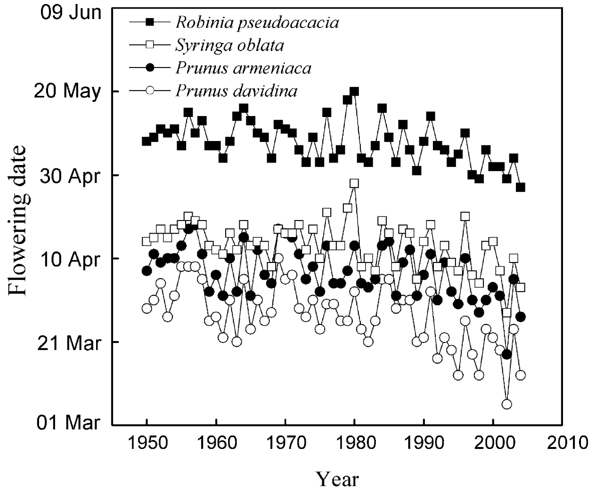

Fig. 2. Time trends of flowering dates in Beijing (1950–2004).

3.2. Time trend of flowering dates

The average flowering dates of *P. davidina*, *P. armeniaca*, *S. oblata* and *R. pseudoacacia* from 1950 to 2004 were 26 March, 5 and 14 April, and 8 May, respectively (Fig. 2). The flowering dates of the four woody species ranged, on average, over 43 days in spring. The four species of tree have different response trends due to different eco-physiological characteristics and growth durations. The beginning of flowering of *P. davidina* occurs in early-spring. As urban climate warming was higher in this period, its flowering date advanced greatly, being very significant in recent decades (Fig. 2). The shift rate of flowering date of *P. davidina* is about 2.9 days/decade, whereas it is about 1.5–2.0 days/decade for the other three species from 1950 to 2004 (from Fig. 2). Flowering dates advanced much more quickly after 1990, and occurred extremely early in 2002.

3.3. Flowering responses to change in temperature

When temperature increases gradually in spring, plants flower successively, indicating a dominant influence of temperature on development. The strongest trend was observed in recent 10 years: it was warmest in spring in 2002 and plants flowered the earliest in over the past 55 years (Figs. 2 and 3). Correlations between flowering dates and temperature were analyzed using data from 1950 to 2004. In this period, a prediction model was fitted and compared with this statistical relationship. The annual timing of flowering is, to a great extent, a response to temperature. Thus, flowering

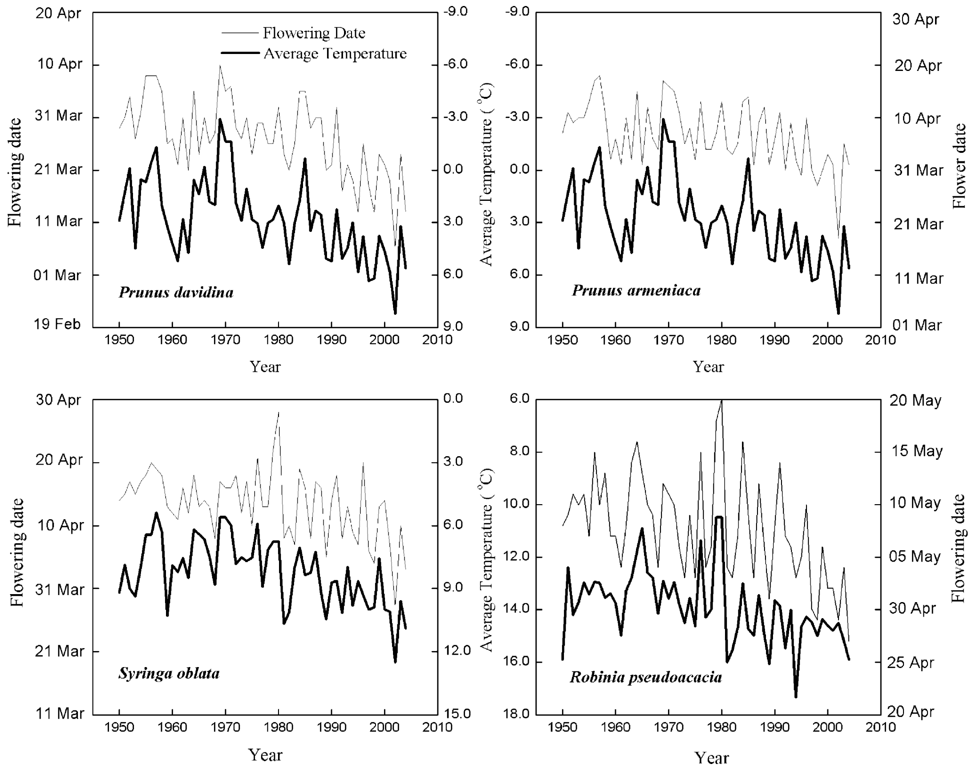

Fig. 3. Response of flowering dates to average temperatures over the 30-day period before average blossom date (1950–2004).

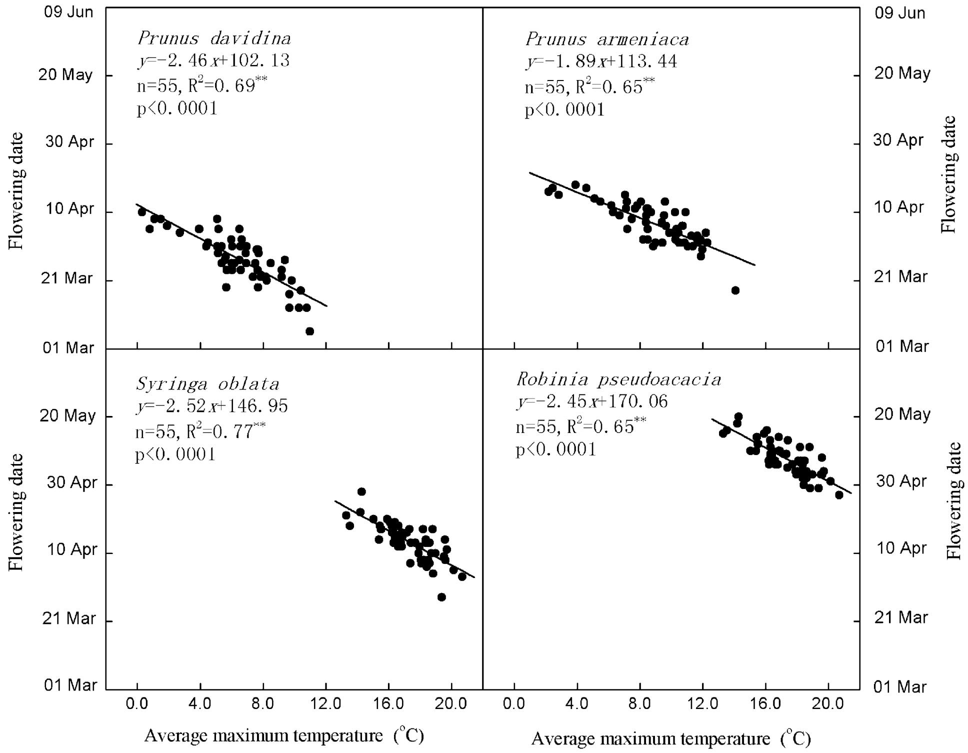

Fig. 4. Relation between flowering dates and average of maximum temperatures over the 30-day period before average blossom date (1950–2004).

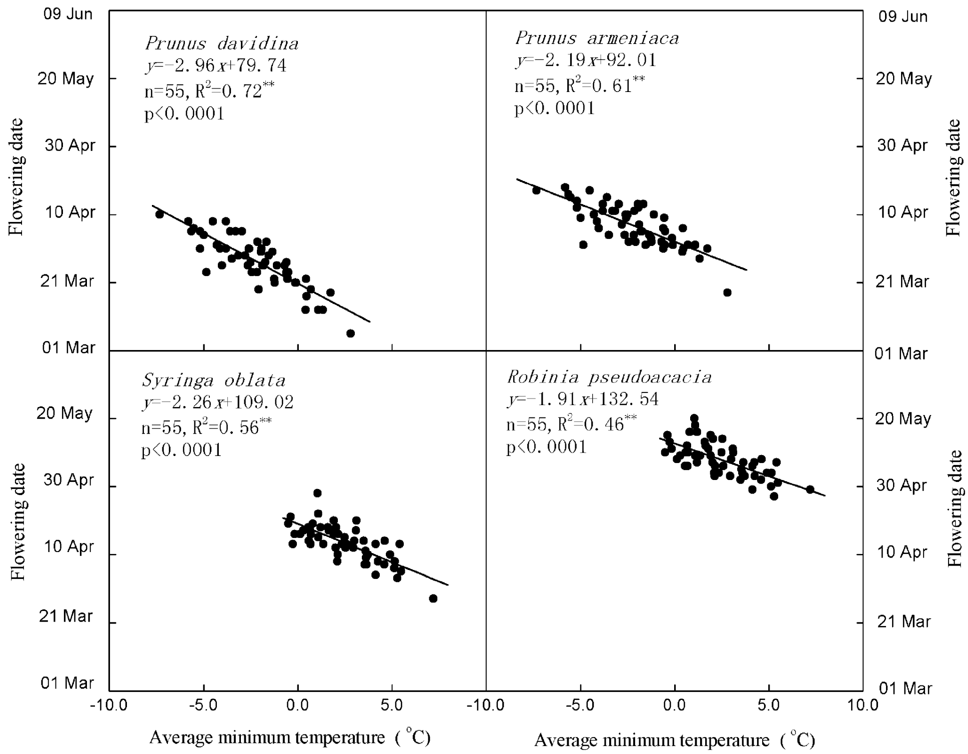

Fig. 5. Relation between flowering dates and average of minimum temperatures over the 30-day period before average blossom date (1950–2004).

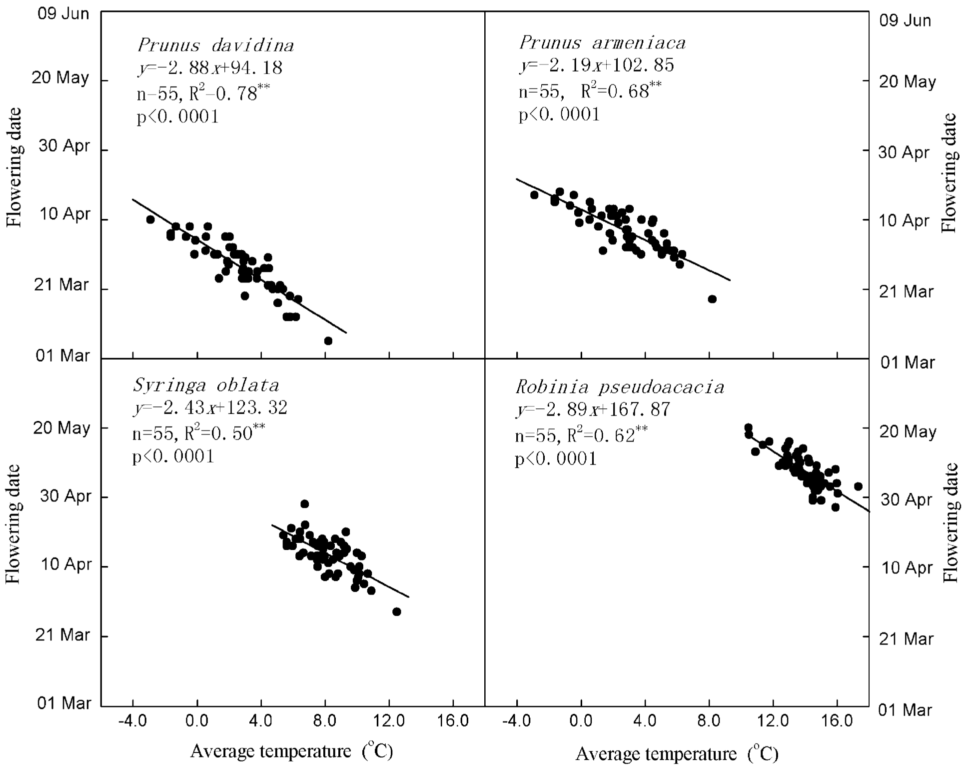

Fig. 6. Relation between flowering dates and average temperatures over the 30-day period before average blossom date (1950–2004).

dates should reflect the thermal regime in Beijing. Flowering dates corresponded well to average temperature in the significant influence period (Fig. 3). Flowering date is closely related to maximum, minimum and average temperatures over the 30-day period before the average blossom date.

The sensitivity of flowering to maximum, minimum and average temperatures are different for specific species (Figs. 4–6, Table 2). Flowering of *P. davidina* and *P. armeniaca* were much more correlated to average temperature ($R^2 = 0.68$–0.78) compared than to maximum and minimum temperatures ($R^2 = 0.61$–0.72). The other two species (*S. oblata* and *R. pseudoacacia*) blossom later and experience warmer seasons, which were much more correlated to maximum temperature ($R^2 = 0.65$–0.77) compared than to average and minimum temperatures ($R^2 = 0.46$–0.62). Regression analysis indicates that advance rates of flowering, in response to temperature increase, are in the range 1.91–2.96 days/°C for T_{min}, 2.19–2.89 days/°C for T_{ave}, and 1.89–2.52 days/°C for T_{max} (Table 2). *P. davidina*, flowering in early-spring, was much more sensitive to minimum and average temperatures (2.88–2.96 days/°C), but less sensitive to maximum temperature (2.46 days/°C). *R. pseudoacacia*, flowering late in warmer seasons, was more sensitive to average and maximum temperatures (2.45–2.89 days/°C), but less sensitive to minimum temperature (1.91 days/°C).

Table 2
Sensitivity of flowering dates to maximum, minimum, and daily average temperatures averaged from 30 days before average blossom date from 1950 to 2004 (from Figs. 4–6)

Tree species	T_{max} (days/°C)	T_{min} (days/°C)	T_{ave} (days/°C)
P. davidina	−2.46	−2.96	−2.88
P. armeniaca	−1.89	−2.19	−2.19
S. oblata	−2.52	−2.26	−2.43
R. pseudoacacia	−2.45	−1.91	−2.89

3.4. Model fitting

Wielgolaski (1999) found that the base temperature in starting dates of development varied for different species. The cardinal temperatures, T_{max} and T_{min} were adjusted within a range to search for goodness of fitting. Finally, 41 and 0 °C were determined for T_{max} and T_{min}, respectively. The flowering data were split into two sets of odd and even years. The non-linear model of temperature response (Eq. (1)) was fitted

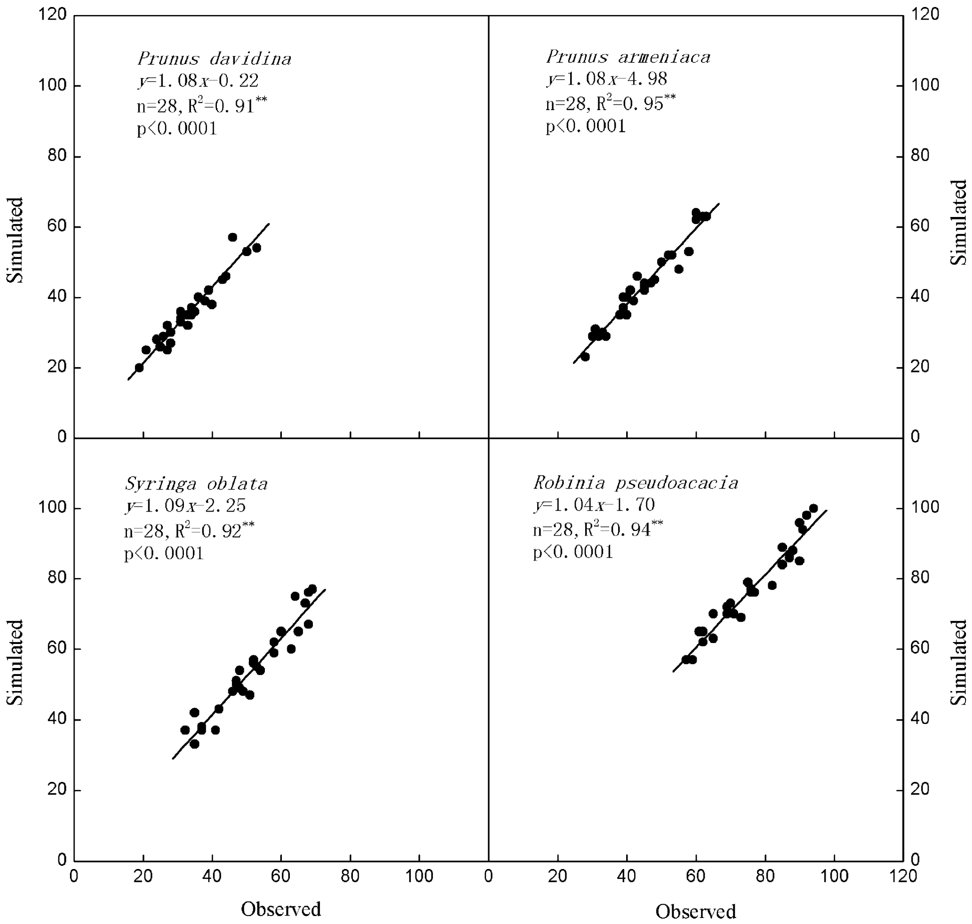

Fig. 7. Fitting of the non-linear model against data of odd years for four tree species, using temperature data from the day when temperature first exceeded 0 °C to the flowering dates.

against data of odd years (Fig. 7). After the parameters were determined the model was tested using the set of even years. The slopes of the linear relationship between simulated and observed dates ranged from 1.04 to 1.08 in model fitting (Fig. 7), and 0.96 to 0.98 for model test (Fig. 8). This demonstrates simulation by Eq. (1) corresponds well with the observed. The determination coefficients ranged from 0.91 to 0.95 for model fitting (Fig. 7), and from 0.82 to 0.95 for model test (Fig. 8). This is significantly better than the correlation with average temperature over the 30-day period before and around blossom, in which the determination coefficients range from 0.50 to 0.78 (Fig. 6).

Statistical methods to establish the correlation between flowering dates and average temperature within certain periods may neglect the non-linear relationship between development and temperature. Also, flowering dates shift in response to climate, but temperature was averaged within certain periods; this may result in the temperature period not matching plant development from initiation to blossom.

4. Discussions

Phenological changes differ between species and climate conditions. Besides ‘water-driven phenology’, phenological phases under a monsoon climate are ‘temperature-driven phenology’. The results show that the significant period of temperature influence is approximately the 30 days before flowering. The level of significance of regression variables depends on climatic characteristics and the sensitive stage of growth. Temperature in the identified periods may influence inter-annual variations in flowering. Temperature in some other periods, which has been found to be statistically insignificant, may be also important for flowering, but contributes less to the variation in

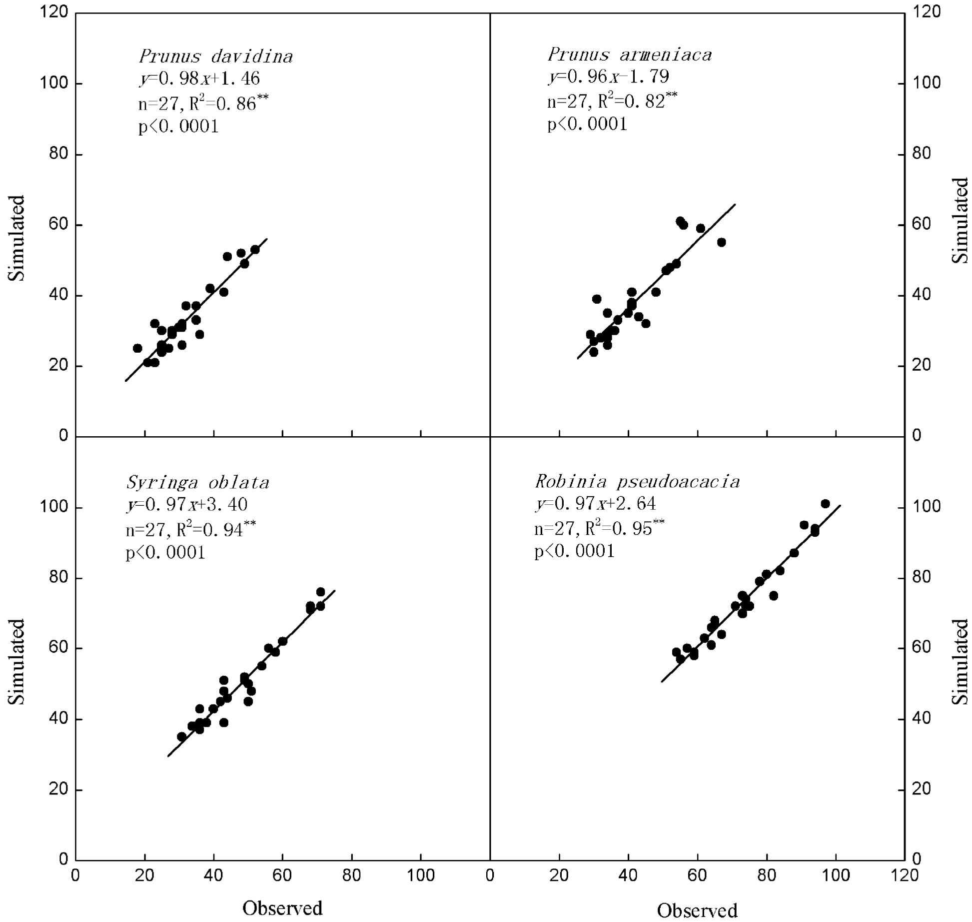

Fig. 8. Testing of the non-linear model against data of even years for four tree species, using temperature data from the day when temperature first exceeded 0 °C to the flowering dates.

flowering dates, because they did not have a large enough variation.

Phenological phases have shown a most significant shift in recent 10 years, but the linear relationship between flowering date and temperature in this study may exist with certain limitation, which is a non-linear curvature approximation (Sparks et al., 2000). Therefore, the simulation model adopted a non-linear relationship between development and temperature, which improved the correlation analysis of temperature influence.

A large variety of phenological models have been presented for specific species, which can be divided into statistical analyses and mechanistic models (for reviews, see Kramer et al., 2000). A popular method of evaluating the response of flowering to temperature is to analyze the correlation between flowering dates and temperature within specific periods (Sparks et al., 2000; Chmielewski and Rötzer, 2001; Lu et al., 2006). As the relationship obtained by statistical regression describes the apparent correlation between phenophases and climatic elements, their capability for predicting the occurrence of phenological events is limited (Figs. 4–6). The simulation model, Eq. (1), may consider the joint effects of temperature and photoperiod, but it is not necessary for simulation in one site because day-length scarcely change each year. The goodness of fitting by the non-linear temperature response model is much better than linear regression between flowering date and average temperature. The determination coefficients of the former are 0.91–0.95 (Fig. 7), whereas they are 0.46–0.78 of the latter (Figs. 4–6). Plants may be stimulated to growth when temperature is higher than 0 °C in spring, when liquid flow is observed in the stem (Wan and Liu, 1979). We also tested 3 and 5 °C for T_{min}, but the association of simulated and observed dates were slightly better when T_{min} = 0 °C. A similar method was also applied to determine the value of T_{max}. Although daily temperature will not reach 41 °C, it exerts a curvature of temperature response. In other words, T_{max} describes a slowing down of the increase in development with temperature in the non-linear model, Eq. (1). The model, Eq. (1), considers the process of plant development and describes the development stages day by day. Therefore, the model can be used to predict flowering date when temperature is provided.

Using the phenological data from 10 central European regions, Rötzer et al. (2000) analyzed and quantified the influence of large-scale climate change and urban climate effects on four spring phenophases for the years 1951–1995. The trends for the period from 1980 to 1995 were much stronger: the pre-spring phenophases on average became earlier by 13.9 days/decade in urban areas and 15.3 days/decade in rural areas.

Warmer than average winter and spring temperatures have been noted over the last century in Western Canada (Beaubien and Freeland, 2000). The first-bloom dates for Edmonton (Alberta) were extracted from four historical datasets and a spring flowering index showed progressively earlier development. For *Populus tremuloides*, a linear trend shows a 26-day/century shift to earlier blooming.

Using data from the International Phenological Gardens for the period 1969–1998 across Europe, Chmielewski and Rötzer (2001) noted that a warming in early-spring (February–April) by 1 °C induced the beginning of the growing season 7 days earlier. The observed extension of the growing season was mainly the result of an earlier onset of spring. An increase in mean annual air temperature by 1 °C led to an extension of 5 days. Using the phenological data from 10 central European regions, Rötzer et al. (2000) analyzed and quantified the influence of large-scale climate change and urban climate effects on four spring phenophases for the years 1951–1995. The trends for the period from 1980 to 1995 were much stronger: the pre-spring phenophases on average became earlier by 13.9 days/decade in the urban areas and 15.3 days/decade in the rural areas. In Estonia, Ahas (1999) analyzed a long-term phenological time series for the impact assessment of climate changes. The study showed that Estonian springs had advanced 8 days on average over the last 80-year period, rates of change being faster in the last 40 years. Kramer et al. (2000) noted that the phenology of the boreal and temperate zone forests is mainly driven by temperature, affecting the timing of the start of the growing season and its duration.

These plant phenological changes are highly correlated with temperature changes, especially in the months before seasonal life-cycle events. It is reported that climate change varied in different regions in China. The North China Plain, including Beijing, has the most significant warming (Wang and Gaffen, 2001). Air temperatures are increasing with an accelerating trend after 1990 for the period 1955–2000, and T_{max} and T_{min} increased at a rate of 1.27 and 3.23 °C (100 years)$^{-1}$ (Liu et al., 2004). Both temperature trends were higher than in the Northern Hemisphere. Temperature, as well as phenological phases, has changed most noticeably after the late 1970s. Urban areas of Beijing have rapidly expanded since China's 'open policy' in 1978. Therefore, the phenological advance reported in this study is attributed to both large-scale climate warming and the effect of the urban heat island. The phenological phases of crops in the North China Plain have also advanced about 4–6 days in the past 10 years, which suggests farmers should sow winter crops (e.g. wheat) in autumn later than usual and apply late-maturing varieties.

5. Conclusions

It can be concluded that:

(1) Early-spring temperature increased faster than late-spring, as influenced by both climate warming and the urban heat island effect in Beijing. Flowering date of early-blossom species, *P. davidina*, advanced much quicker than other late-blossom species, which tend to stretch the flowering interval among species. The flowering date of *P. davidina* advanced by 2.9 days/decade, while others advanced by 1.5–2.0 days/decade during 1950–2004.

(2) The flowering sensitivity of four tree species under a monsoon climate to daily maximum, minimum and average temperature, is 'species-specific'. Flowering of *P. davidina* and *P. armeniaca* were more correlated to average temperature, while *S. oblata* and *R. pseudoacacia*, blossoming later and experiencing warmer seasons, were more correlated to maximum temperature.

(3) A non-linear temperature response model may precisely predict flowering, assuming development starts from temperature above 0 °C. Its performance is better than the empirical linear regression between flowering dates and spring average temperature.

Acknowledgements

We dedicate this paper to Prof. Kezhen Zhu (1890–1974), the former vice president of Chinese Academy of Sciences, for his leadership and organization of the Phenological Network of China, and his observation in Beihai Park from 1950 to 1973. This work is supported by National Natural Science Foundation of China (no. 40328001).

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