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Clarifying springtime temperature reconstructions of the medieval period by gap-filling the cherry blossom phenological data series at Kyoto, Japan

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Abstract

We investigated documents and diaries from the 9th to 14th centuries to supplement the phenological data series of the flowering of Japanese cherry (*Prunus jamasakura*) in Kyoto, Japan, to improve and fill gaps in temperature estimates based on previously reported phenological data. We then reconstructed a nearly continuous series of March mean temperatures based on 224 years of cherry flowering data, including 51 years of previously unused data, to clarify springtime climate changes. We also attempted to estimate cherry full-flowering dates from phenological records of other deciduous species, adding further data for 6 years in the 10th and 11th centuries by using the flowering phenology of Japanese wisteria (*Wisteria floribunda*). The reconstructed 10th century March mean temperatures were around 7 °C, indicating warmer conditions than at present. Temperatures then fell until the 1180s, recovered gradually until the 1310s, and then declined again in the mid-14th century.

Key words: Climatic reconstruction; Kyoto; Phenology; Cherry blossom; Wisteria flower

Introduction

Phenological data observed continuously, mainly in Europe, since the 18th or 19th centuries, have been analyzed from a climatological perspective (Sparks and Carey 1995; Ahas 1999; Defila and Clot 2001), and historical records of the phenological characteristics of plants have been used to reconstruct long-term changes in climatological factors, mainly temperature. For example, a data series of grape ripening and harvesting in France since the 14th century, one of the longest climatic reconstruction series based on European phenological events (Chuine et al. 2004), is well known for showing changes in spring–summer temperature anomalies.

In Kyoto, Japan, old diaries and chronicles describe and record the dates of cherry blossom viewing, and investigators have used these records to assemble a phenological data series of full-flowering of *Prunus jamasakura* (Taguchi 1939; Arakawa 1956; Sekiguchi 1969; Aono and Omoto 1993, 1994; Aono and Kazui 2008). *Prunus jamasakura* is a native tree species of Japan with the common name Japanese cherry; use of the contraction "cherry" herein refers to this species. Recently, Aono and Kazui (2008) compiled cherry flowering data at Kyoto covering 732 years between A.D. 812 and 2005 and used them to reconstruct the March mean temperature series since the 9th century. From 1401 to 2005, phenological data were available for more than 70% of the years, making reliable temperature reconstruction possible. Within this last 600-year period, three cold periods with springtime temperatures 3 °C lower than at present and synchronous with three solar minima, the Spoerer, Maunder, and Dalton minima, have been recognized in the reconstructed temperature series. This 600-year period also includes the cold period known as the Little Ice Age.

Another notable historical climatic event is the Medieval Warm Period (9th to 13th centuries). Many studies using various proxies for temperature or precipitation have suggested that the Medieval Warm Period had a climatic counterpart in Asia during 800–1250 (e.g., Kitagawa and Matsumoto 1995; Agnihotri et al. 2002; Liu et al. 2006; Sinha et al. 2007; Fengming et al. 2008).

Phenological events can also be used to reconstruct medieval temperature changes, provided that sufficient phenological data can be gleaned from the many old documents. However, in our previous study (Aono and Kazui 2008), phenological data were available for only 30–50% of the years from the 12th to the 14th centuries. As a result, the reconstructed temperatures strongly fluctuated with relatively wide confidence intervals, making continuous reconstruction of climate change impossible for the period from the 9th to the 11th centuries.

The main purpose of this study was to use springtime phenological data from Kyoto to reconstruct a more reliable and continuous springtime (March) temperature data series, focusing on the medieval period before A.D. 1400. We obtained additional phenological data on the full-bloom dates of *Prunus jamasakura* from descriptions in old documents, as in our previous study. To complement the cherry blossom data, we also investigated contemporaneous records of the flowering of other deciduous species, namely, wisteria (*Wisteria floribunda*), Japanese apricot (*Prunus mume*), Japanese kerria (*Kerria japonica*), and woody peony (*Paeonia suffruticosa*).

In this paper, we compare our newly supplemented reconstructed temperature series with our previous series and with other previous results. We then offer a perspective on possible directions that further phenological investigation at Kyoto might take for reconstruction of springtime temperatures.

Phenological data acquisition

Investigation of cherry flowering phenology

We investigated the flowering of cherry at Kyoto (35°00'N, 135°40'E) from A.D. 801 to 1400. Because Kyoto was the capital of Japan from 794 to 1868, many old diaries and chronicles of events in Kyoto, written by many people of various standings in society, have been preserved. Many descriptions in the old diaries suggest that even during this early historical period, cherry blossom viewing parties were held when the cherry trees were in full bloom. *Prunus jamasakura* trees are generally in full bloom for only 2–4 days. We compiled the dates, according to the Japanese lunar calendar, on which cherry blossom viewing parties were held or on which the trees were observed to be in full bloom, and then converted them to the day of year (DOY) according the modern Gregorian calendar. We regarded these dates as the first date that *Prunus jamasakura* came into full-bloom, as discussed by Aono and Kazui (2008).

Figure 1 shows the cherry flowering data for each century as acquired by the present and previous works, including those for the 15th to 21st centuries. In the present investigation, we acquired full-flowering dates for an additional 51 years in the period from the 9th to the 14th century: 24 days from old diaries, 13 from chronicles, and 14 from Japanese poetry. These, when added to those we compiled previously (Aono and Kazui 2008) and with substitutions for 9 years made after considering the validity of various recorded descriptions, yielded a total of 224 data points for the 9th to 14th centuries.

The newly acquired data included data for 7 years in the 9th century, the first in that century since the investigation of Taguchi (1939), and data for 23 years in the 13th century. When these data are added to those acquired previously, the full-flowering dates in more than half the years from the 12th to the 14th centuries became available. In spite of our intensive investigation of various old diaries, chronicles, and poems in this study, we were unable to find any phenological data for the years between 1040 and 1080. In Kyoto, many medieval documents have been lost as a result of natural disasters and conflagrations. Table 1 shows the full-flowering dates acquired in each century. From the 9th through the 14th centuries, we acquired an average of 37 cherry full-flowering dates per century. The standard deviation, which ranged from 5.2 to 6.9 days, varied little over these six centuries.

Figure 2 shows the available data on interannual variation of the full-flowering dates of *Prunus jamasakura* from the 9th to the 14th centuries. Dates added by the present study (solid circles) fall primarily in the second half of the 9th century and the first half of the 13th century, filling gaps in the temperature reconstruction for the medieval period and thus possibly improving its accuracy. For reference, the full-flowering dates from the 15th to the 21st centuries acquired previously (Aono and Kazui 2008) are also shown in Fig. 2. The data density from the 9th century to the 11th century is quite low compared with that after A.D. 1400.

Supplementation by wisteria flowering phenology

Previously, we had found few documented full-flowering dates for cherry from before the 11th century. In Japan, the dates of flowering of some species other than cherry have also been recorded since ancient times. Moreover, Rutishauser et al. (2007) compared springtime phenological observations among several plant species and built an indexed phenological data series for a statistical "spring plant". Their results suggest that the phenological record of one species can be used to complement those of other species that occur at almost the same time of year.

In Kyoto, flowering phenologies of other deciduous species, such as wisteria, Japanese apricot, Japanese kerria, and woody peony, are also recorded in old documents. Accounts of viewing parties of flowering Japanese wisteria (*Wisteria floribunda*), in particular, were often recorded as far back as the medieval period. Therefore, to help fill the gaps in the cherry blossom phenological data record for the 10th and 11th centuries, when data were available for only about a quarter of the years, we supplemented the cherry data with phenological data of the flowering of

Japanese wisteria.

Japanese wisteria is a deciduous woody climbing vine native to rural and mountainous areas of Japan. This species had been introduced as an ornamental tree to the Imperial Palace gardens by the 10th century, as attested by many old documents. In the medieval period, ornamental wisteria vines were not supported by garden pergolas as in modern Japan but were allowed to climb trees such as pine.

In Kyoto, full-flowering of wisteria occurs between late April and mid-May, 2 or 3 weeks later than the flowering of cherry. Moreover, the wisteria flowering date in Japan is greatly affected by springtime temperatures (Goi 1982), particularly the temperatures after the middle of February (Aono and Omoto 1992), meaning the date can be estimated from springtime temperatures alone. Since the full-flowering date of *Prunus jamasakura* in Kyoto also depends on temperatures after the middle of February (Aono and Kazui 2008), it is reasonable to infer that the periods during which temperature affects the flowering dates of these two species greatly overlap. Therefore, we expected that the interannual variation of the full-flowering dates of these two species would show some correlation.

We acquired the dates on which descriptions of the full-flower status or viewing parties of wisteria were recorded in the same way as for cherry, regarding them as the wisteria full-flowering dates. Since wisteria generally is at full flower for one week, 2 or 3 days longer than cherry, the uncertainty in its full-flowering phenological data might be larger. However, wisteria flower viewing was popular during several periods both during and after the medieval period. We therefore used those years for which we obtained full-flowering dates of both cherry and wisteria to calibrate the relationship between the full-flowering dates of the two species. We first searched for wisteria flowering data from the 10th to the 21st centuries by surveying old diaries, chronicles, and newspapers, and then used cherry flowering data acquired in the present work and in our previous study (Aono and Kazui 2008) to calibrate the wisteria phenology over that period.

Phenological data sets for 23 years from the 12th to the 21st centuries were available for this calibration (Table 2). The oldest data set was obtained for 1180 and the latest one was for 2007. Figure 3 shows the relationship between the full-flowering dates of cherry and those of wisteria. We obtained four data sets, each covering two or three centuries, and plotted each data set using a different symbol. We obtained several full-flowering dates of the two species during 1995–2007 from newspapers. Dates from the 20th and 21st centuries (open triangles) are earlier in the year than those from earlier centuries, reflecting recent warm spring temperatures, and in general the data points in each data set are clustered. Therefore, we used the data of all four data sets to relate the full-flowering dates of cherry to those of wisteria.

The full-flowering dates of the two species were significantly correlated ($P < 0.001$) as shown by equation (1):

$$B_P = 0.57B_W + 29.46 \qquad (r^2 = 0.53) \ , \qquad (1)$$

where B_W (DOY) is the full-flowering date of wisteria and B_P (DOY) is that of cherry. The root mean square error of estimated B_P was 3.4 d. Thus, for years in which only the full-flowering date of wisteria was available (5 years in the 10th century and 1 year in the 11th century), we used equation (1) to estimate the full-flowering date of cherry in the same year (Figs. 1 and 2).

We also investigated the flowering phenologies of other deciduous species, Japanese apricot (*Prunus mume*), Japanese kerria (*Kerria japonica*), and woody peony (*Paeonia suffruticosa*), in the same way, but we were not able to supplement the cherry flowering phenology with these other flowering phenologies for reasons described in the second section of the chapter on results and discussion.

Temperature reconstruction method

We estimated the March mean temperature by reverse application of the DTS (number of Days Transformed to Standard temperature) method (Konno and Sugihara 1986), which calculates a cumulative daily temperature index as an exponential function of daily mean temperature. The DTS model has been used to estimate the flowering dates of several ornamental (Aono and Omoto 1990, 1992; Aono and Moriya 2003) and deciduous fruit tree (Aono and Sato 1996; Honjo et al. 2006) species, as well as the budburst dates of many native Japanese broad-leaved tree species (Fujimoto 2007).

The daily DTS value is a ratio expressing the amount of growth that occurs in one day at the actual daily mean temperature relative to that which occurs at a standard temperature. The DTS value on the *j*th day of the *i*th year is calculated as follows:

$$(t_s)_{ij} = \exp\left\{\frac{E_a(T_{ij} - T_s)}{R \cdot T_{ij} \cdot T_s}\right\} \quad (2)$$

where T_{ij} is the daily mean temperature on the *j*th day of the *i*th year, T_s is the standard temperature (288.2 K), R is the universal gas constant (8.314 J mol^{-1} K^{-1}), and E_a is the temperature characteristic (J mol^{-1}), which is a parameter expressing the responsiveness of flower bud development to temperature. The estimated date of the phenophase of interest (full flowering) is the day on which the cumulative DTS value reaches a predetermined mean value. Aono and Kazui (2008) tuned this model for estimation of the full-flowering date of *Prunus jamasakura* at Kyoto for the period from 1911 to 1940, set as the calibration period, and determined DOY 42 to be a suitable starting date for DTS accumulation and 56 kJ mol^{-1} to be a suitable value for E_a. This parameterization enabled them to accurately estimate the full-flowering dates during 1901–2005, with an RMSE of 2.5 days. Aono and Kazui (2008) describe the determination of suitable values of variables for the DTS method in detail.

To estimate March mean temperatures from phenological data, an inverse of the DTS method should be applied. In this method, a constant temperature anomaly value is added to the normal daily mean temperature value. The value of the anomaly is adjusted for each year so that the cumulative DTS value on the actual full-flowering day of the year agrees with the predetermined normal cumulative value (DTS_N) on the full-flowering date. For a year in which full flowering of *Prunus jamasakura* was actually observed on day B (DOY), the estimated temperature anomaly, ΔT (K), is adjusted as follows:

$$\sum_{j=D}^{B} \exp\left\{\frac{E_a(T_{Nj} + \Delta T - T_s)}{R \cdot T_s \cdot (T_{Nj} + \Delta T)}\right\} \approx DTS_N \qquad (3)$$

where T_{Nj} is the normal daily mean temperature on the jth day, and D is the day on which accumulation starts (starting date, DOY 42). In our previous study, we calibrated the temperature and full-flowering phenological data using data from 1911 to 1940. In this study, we thus used the sum of the March mean temperature averaged over 1911–1940 (6.4 °C) and the derived temperature anomaly, ΔT, of a year as the estimated March mean temperature for that year.

Comparison of actual temperatures with those estimated, after smoothing by local linear regression over 31-year spans, showed a good fit, with RMSE of only 0.1 °C for both the calibration period (1911–1940) and the 50 years from 1941 to 1990. We previously determined that this method is applicable to both instrumental (after 1881) and historical (before 1881) data (Aono and Kazui 2008).

Results and discussion

Temperature reconstructions

Figure 4 shows three time series of changes in the March mean temperature: that reconstructed by Aono and Kazui (2008) and those reconstructed in this study using phenological information from cherry alone and from both cherry and wisteria. The reconstructions are shown as curves smoothed by local linear regression over 31-year time spans to allow discussion of long-term climate changes. To indicate the accuracy of the reconstructed temperatures, 95% confidence intervals of the smoothed values are also shown. When fewer data points were used in a given time span for the smoothing, the confidence interval is wider, implying more uncertainty in the smoothed temperature. The horizontal broken line in each panel in Fig. 4 indicates the present normal March mean temperature of 7.1 °C, derived by subtracting an urban warming bias of 1.1 °C by the method of Omoto and Hamotani (1979), who calculated the urban warming bias as the difference between the actual temperature and estimates of the temperature under assumed natural (non-urbanized) conditions. We used the temperature at a control site, Hikone, 50 km from Kyoto, in this analysis. We estimated the temperature at Kyoto under assumed natural conditions as the sum of the original (natural) average temperature difference that existed between Kyoto and Hikone until the 1920s and the yearly temperature observations at the Hikone control site after the 1930s.

The reconstructed temperature series derived from only the cherry blossom data (Fig. 4b) was discontinuous during 890–940, but by supplementing the cherry phenological series with the wisteria phenological data, we were able to obtain at least three data points in each 31-year span smoothed by local linear regression, as required by the smoothing procedure. Thus, with six additional data points from the wisteria phenology filling gaps in the cherry blossom phenological data, we were able to construct a continuous temperature series over the 140-year period from 890 to 1030 (Fig. 4c).

Reconstructed temperatures for the 10th century were generally high, around 7 °C, with a peak value of 7.6 °C. Subsequent to the 10th century, the smoothed temperatures did not again exceed this warm peak until the second half of the 20th century. The warm springtime temperatures in the middle of the 10th century were almost the same or somewhat higher than present normal temperatures after subtracting the urban warming effect. The reconstructed temperature series shows a cooling trend from the middle of the 10th century until the early 11th century. The 10th century warm peak in the estimated temperature series of Kitagawa and Matsumoto (1995) approximately coincides with the warm peak found in this study. However, our series has only 31 data phenology points in the 10th century, and five of these are estimates derived from wisteria phenology. Thus, the confidence intervals in this period are wider than those in later centuries. The accuracy of our reconstructed 10th century temperatures therefore requires further confirmation.

In the early 11th century, we found an apparent slight declining trend in the reconstructed temperature series both in our present (Fig. 4b and 4c) and previous (Fig. 4a) studies. However, we were not able to determine subsequent 11th century temperature changes because of a lack of phenological data for the middle of the century, from 1040 to 1080. From the 1080s to the 1180s, the temperature reconstructions of this study (Fig. 4b and 4c) showed an overall cooling trend with a couple of small peaks in the middle of 12th century.

The temperature series reconstructed by using only cherry blossom phenological data (Fig. 4b) fluctuates less during 1180–1250 than our previous temperature series (Fig. 4a) because this 70-year period includes 23 new cherry full-flowering dates, Thus, the combined data cover more than half of the years in this period, and as a result, the 95% confidence intervals for the first half of the 13th century narrow to within ±1.2 °C (Fig. 4a and 4b).

The more numerous cherry phenological data for 1180–1250 allowed the reconstruction of a continuous smoothed temperature series from the end of the 11th century to the end of the 13th century. This series shows a warming trend from the 1180s to the 1310s. At the beginning of 14th century, a peak value of 7.1 °C was estimated. In the present study, the reconstructed temperatures for the 13th century range from 5.5 to 7.0 °C, which are 0.5–2.0 °C lower than the estimates for the 10th century warm peak, and those for the first half of the 13th century are 1.0–1.5 °C lower than those estimated in our previous study (Fig. 4a). The 13th century temperature trends determined in this study may be more reliable than those of our previous study because we analyzed a larger number of phenological data points. After the 1310s, the reconstructed temperatures decline rapidly.

The general pattern of the reconstructed temperatures in the present study is consistent with the pattern found by Kitagawa and Matsumoto (1995) in their analysis of $\delta^{13}C$ values of Japanese cedar, and also shows similarities with reconstructed Indian summer monsoon precipitation changes (Sinha et al. 2007), suggesting that warm, humid conditions prevailed in Asia during the Medieval Warm Period.

Approaches for further investigations

In this study, we used cherry phenological data supplemented with wisteria flowering data. Other phenological investigations for reconstruction of the climate in the medieval period are possible; we discuss some of these below, referring to the phenologies of other species examined in the course of this study.

From the 9th to the 11th century, the flowering of the Japanese apricot (*Prunus mume*), a deciduous species of the same genus as Japanese cherry, was often observed and recorded in old documents. The oldest phenological data for the Japanese apricot tree showed a full-flowering date of DOY 64 (March 4) A.D. 848. Therefore, we attempted to use the full-flowering phenology of the Japanese apricot to estimate that of cherry, similar to our use of wisteria phenology. We acquired the dates on which the full-flower status or viewing parties of Japanese apricot flowers were recorded and compared this data set with the cherry blossom phenology data set to calibrate the relation between the full-flowering dates of the two species. Phenological data sets for both Japanese apricot and cherry were obtained for 28 years scattered from the 10th to the 17th centuries (from 949 to 1680).

The full-flowering dates of Japanese apricot, however, were not significantly correlated with those of cherry (Fig. 5), perhaps because many varieties of Japanese apricot exist with varying responses to temperature. Most early flowering varieties bloom in January or February at Kyoto, and late flowering varieties generally bloom from February to April. Thus, full-flowering dates of the early flowering varieties cannot be expected to be closely related to temperatures in March. Temperatures in November or December of the previous year generally affect the flowering phenology of the early flowering varieties of Japanese apricot, whereas temperatures of the previous year do not strongly affect the flowering phenology of cherry trees (Aono and Sato 1996). Moreover, the early flowering varieties of Japanese apricot require not only warmth during November to December, to promote their bud development, but also cold temperatures, which break rest (endodormancy) of their buds. As a result, the responses of the flower buds to temperature are complex. On the other hand, late-flowering varieties show a temperature response similar to that of cherry. Most old documents, however, do not clearly indicate what variety of Japanese apricot was being observed but mix information of several varieties, making it difficult to use Japanese apricot phenology to fill gaps in the cherry blossom phenology.

In contrast, the full-flowering dates of Japanese kerria (*Kerria japonica*; family Rosaceae) show a close relationship with those of cherry (Fig. 6). Japanese kerria is a common deciduous shrub native to Japan, and its full-flower status was sometimes recorded in old diaries. It generally blooms between the flowering times of cherry and wisteria in Kyoto. The oldest phenological data acquired for kerria were from 1226 and the latest were from 2007 (Table 3). Phenological data sets for 17 years were available for the calibration (Fig. 6), and the relation between the two data sets was consistent from historical time to the present. The full-flowering dates of kerria and cherry were significantly correlated ($P < 0.001$), as shown by equation (4):

$$B_P = 0.71 B_K + 17.44 \qquad (r^2 = 0.69), \tag{4}$$

where B_K (DOY) is the full-flowering date of Japanese kerria. These results suggest that the period during which temperature affects the full-flowering date of kerria greatly overlaps that of cherry.

Thus, the flowering phenology of Japanese kerria can, like that of wisteria, potentially supplement records of the full-flowering of cherry. However, in this study we found no records of the flowering phenology of kerria from the 9th to 12th centuries. We therefore could not use full-flowering dates of kerria to fill gaps in our medieval temperature series.

We also attempted to use the flowering phenology of woody peony (*Paeonia suffruticosa*) to estimate full-flowering dates of cherry. Flowering of woody peony was also sometimes observed and recorded in old documents, and we investigated and analyzed woody peony flowering phenology in the same way as with the other species, acquiring a phenological data set covering 14 years, scattered from the 12th to the 19th century. However, the full-flowering dates of woody peony were not significantly related to those of cherry (data not shown).

Most medieval climate reconstructions that can be compared with the present study are based on temperature proxies derived from measurements of sediment or tree rings, and it is comparatively more difficult to infer the medieval climate from only cherry blossom phenology. However, continued investigation of old documents and acquisition of more phenological data for the flowering of cherry, wisteria and Japanese kerria might make it possible to improve the reconstruction of temperatures and to fill more gaps in the medieval spring temperature series at Kyoto. If no additional phenological data can be acquired, it may still be possible to combine phenological analysis with information on specific weather conditions (e.g., rainy and snowy days) recorded in some old medieval diaries to improve our reconstruction of the medieval climate in Japan.

Concluding Remarks

We improved our reconstruction of springtime temperatures at Kyoto during the 9th to the 14th centuries by using phenological data, mainly for cherry blossoms. Our additional survey of cherry phenological data supplemented with wisteria phenology filled some gaps in previous reconstructions of springtime temperatures in the medieval period. Temperature estimates showed two warm temperature peaks of

7.6 °C and 7.1 °C, in the middle of the 10th century and at the beginning of the 14th century, respectively. The reconstructed 10th century temperatures are somewhat higher than present temperatures after subtracting urban warming effects. The general pattern of change in the reconstructed temperature series in this study is similar to results reported by previous studies, suggesting a warm period in Asia corresponding to the Medieval Warm Period in Europe.

We confirmed that the flowering phenologies of wisteria and Japanese kerria can be used to estimate the contemporaneous cherry blossom phenology. However, a large gap remains in the phenological data during 1040–1080 that we could not fill in this study. Further investigation of the springtime phenology of other deciduous species might be helpful in filling this large gap. Furthermore, to complete the medieval temperature series reconstructed using phenological data, it will likely be necessary to combine phenological data with other types of data, such as daily weather records, from old diaries.

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Captions for figures

Fig. 1 Number of phenological observations per century according to published and newly acquired data

Fig. 2 Interannual variation in the full-flowering dates of Japanese cherry, *Prunus jamasakura*, at Kyoto, acquired from old documents. The upper panel shows the data series for the present study period from A.D. 801 to 1400, and the lower one shows the series from 1400 to 2008, previously reported by Aono and Kazui (2008). Full-flowering dates estimated from the full-flowering dates of wisteria (*Wisteria floribunda*) are shown by crosses (×)

Fig. 3 Relationship between full-flowering dates of Japanese cherry (*Prunus jamasakura*), B_P, and those of wisteria (*Wisteria floribunda*), B_W. A linear regression equation was derived by using the data points of all four data sets (divided according to time period)

Fig. 4 Mean reconstructed March temperatures for the medieval period (9th–14th centuries) at Kyoto. Thicker lines indicate larger numbers of phenological data points in each 31-year span used for the local linear regression procedure. The 95% confidence intervals of the smoothed values are shown by dotted lines. (a) Results reported by Aono and Kazui (2008), and results of the present study from (b) cherry blossom data only and (c) data from both Japanese cherry and wisteria. The horizontal broken line in each panel indicates the present normal temperature of 7.1 °C, which has been corrected for the urban warming bias

Fig. 5 Relationship between the full-flowering dates of Japanese cherry (*Prunus jamasakura*), B_P, and those of Japanese apricot (*Prunus mume*), B_M

Fig. 6 Relationship between full-flowering dates of Japanese cherry (*Prunus jamasakura*), B_P, and those of Japanese kerria (*Kerria japonica*), B_K. The linear regression equation was derived by using the data points of all four data sets (divided according to time period)

Table 1 Full-flowering dates of Japanese cherry by century

Century	The number of data acquired in this study (for cherry blossoms)	Averages (DOY)	Standard deviation (d)	Number of data added as estimates by wisteria phenology
(Present study)				
9	14	103	5.2	0
10	26	101	6.9	5
11	26	105	6.8	1
12	53	107	6.0	0
13	53	105	5.7	0
14	52	105	6.7	0
Total	224			6
(Previous study; Aono and Kazui (2008))				
15	87	103	5.9	-
16	93	107	6.5	-
17	86	106	6.8	-
18	95	106	6.1	-
19	90	107	6.0	-
20 - 21	99	101	4.8	-

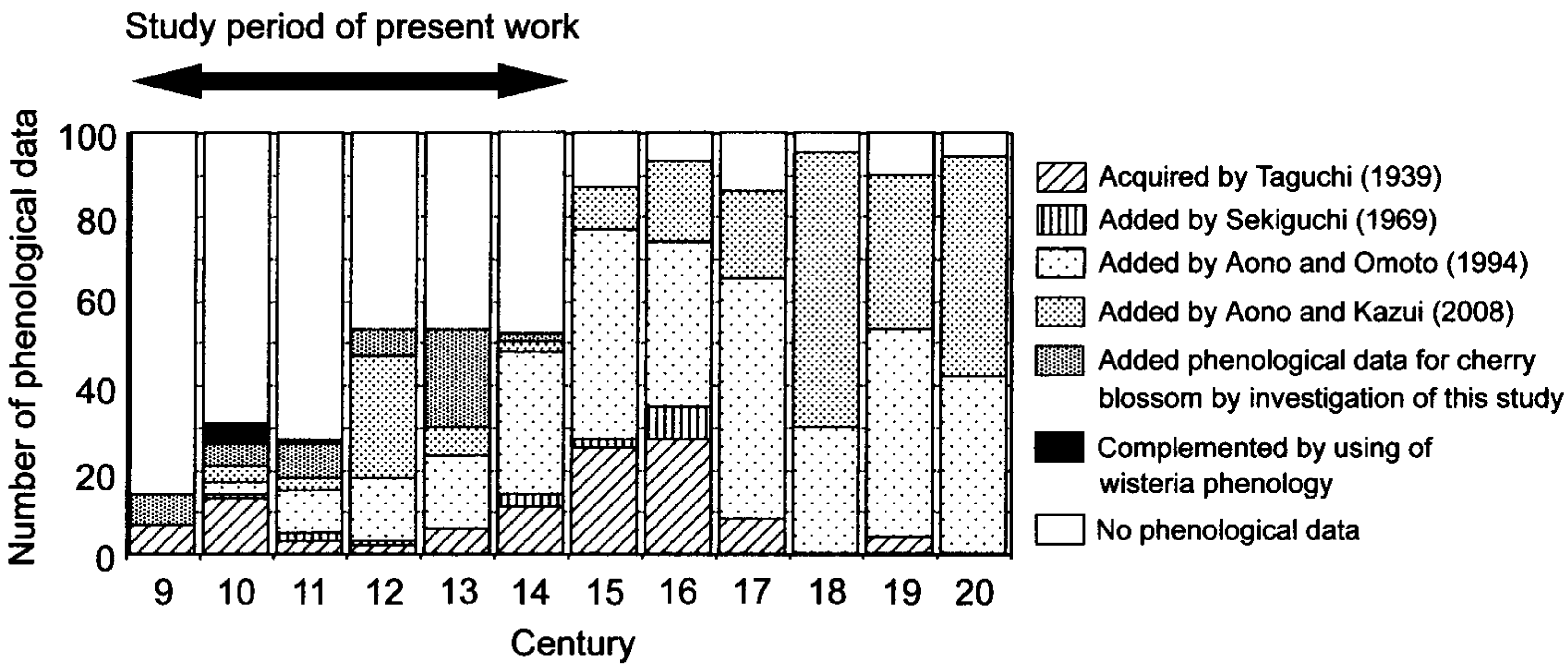
Table 2 Contemporaneous data sets of the full-flowering dates of Japanese cherry and wisteria

Year	Full-flowering dates		Year	Full-flowering dates	
	Cherry	Wisteria		Cherry	Wisteria
AD	(DOY)	(DOY)	AD	(DOY)	(DOY)
1180	98	124	1995	99	122
1377	105	125	1998	91	112
1379	103	131	2001	96	119
1485	94	122	2002	91	110
1486	99	119	2003	98	117
1487	93	114	2004	92	115
1488	103	124	2005	99	117
1490	97	126	2006	98	124
1524	109	126	2007	97	119
1605	105	137			
1747	101	126			
1749	100	132			
1756	109	127			
1861	102	120			

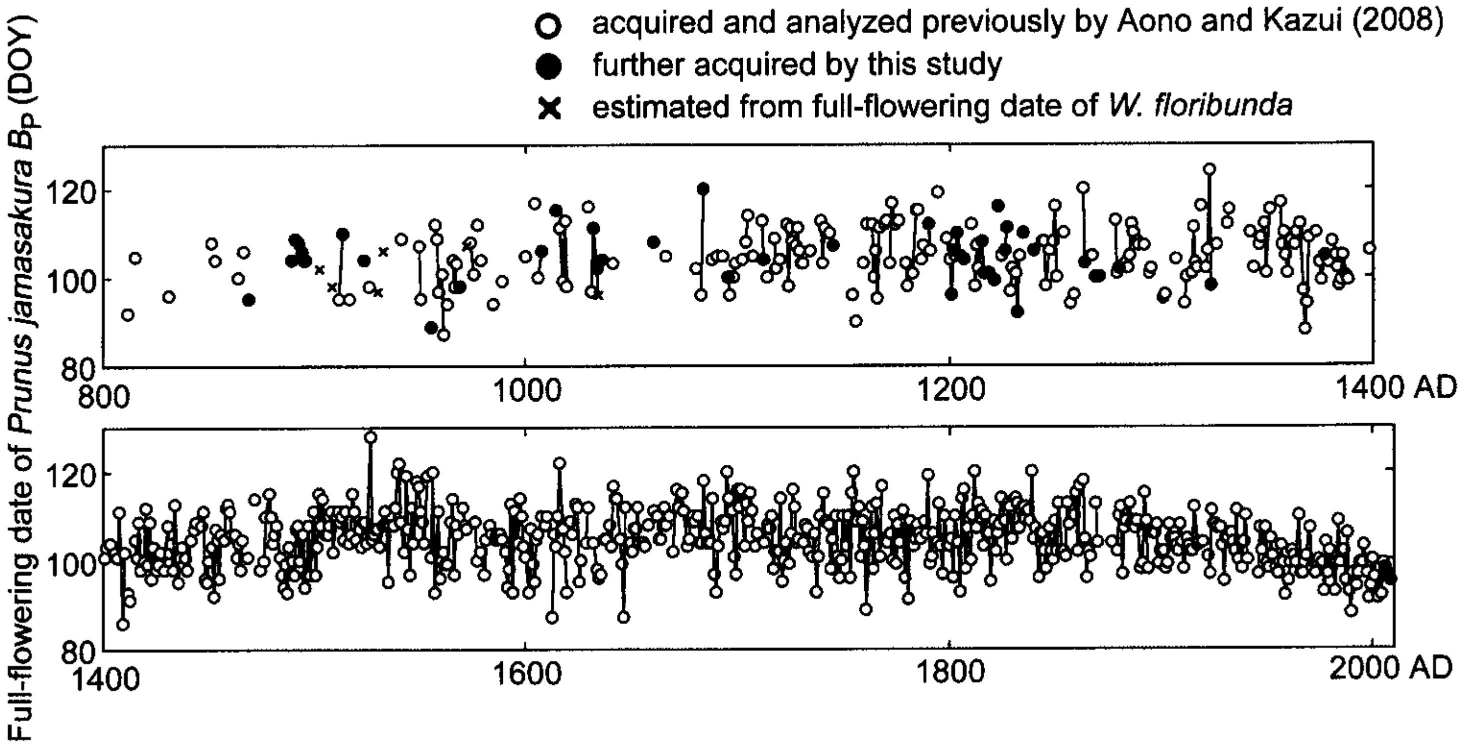
Table 3 Contemporaneous data sets of the full-flowering dates of Japanese cherry and Japanese kerria

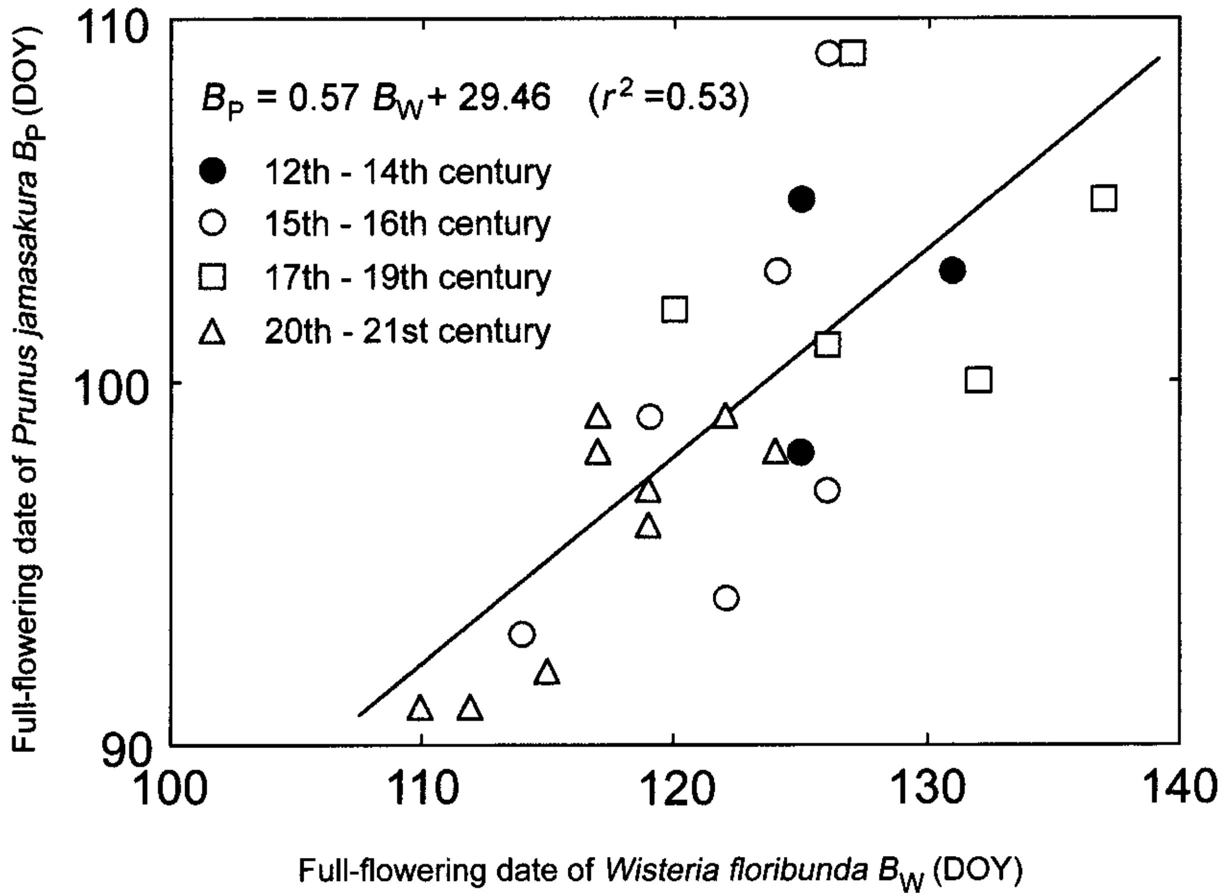
Year	Full-flowering dates		Year	Full-flowering dates	
	Cherry	Kerria		Cherry	Kerria
AD	(DOY)	(DOY)	AD	(DOY)	(DOY)
1226	106	118	1997	97	110
1520	105	119	1998	91	106
1791	99	114	1999	94	109
1799	103	121	2001	96	114
1800	103	116	2002	91	102
1802	96	112	2003	98	114
1808	98	108	2004	92	108
			2005	99	115
			2006	98	120
			2007	97	115

Aono and Saito, Figure 1

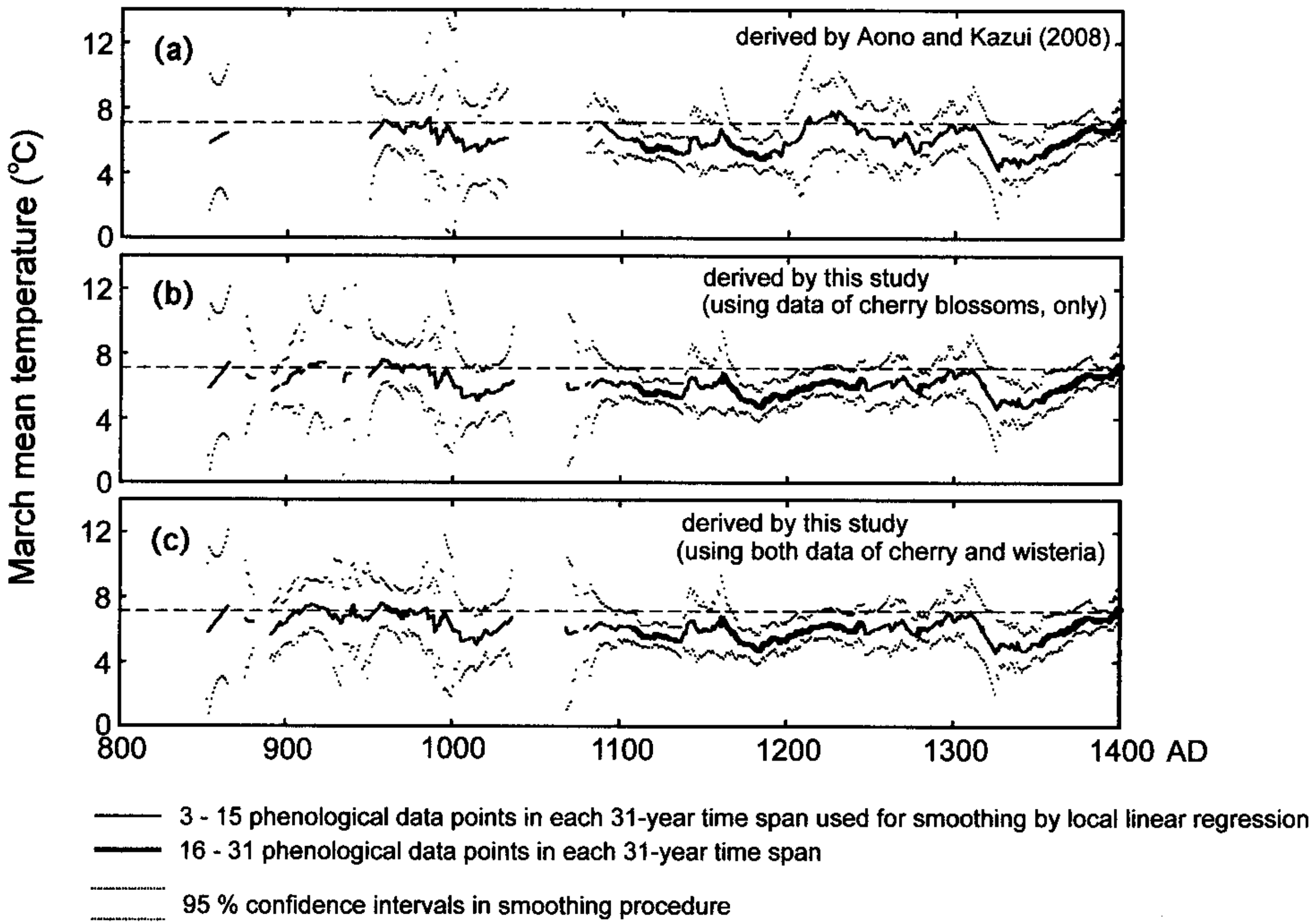


Aono and Saito, Figure 2

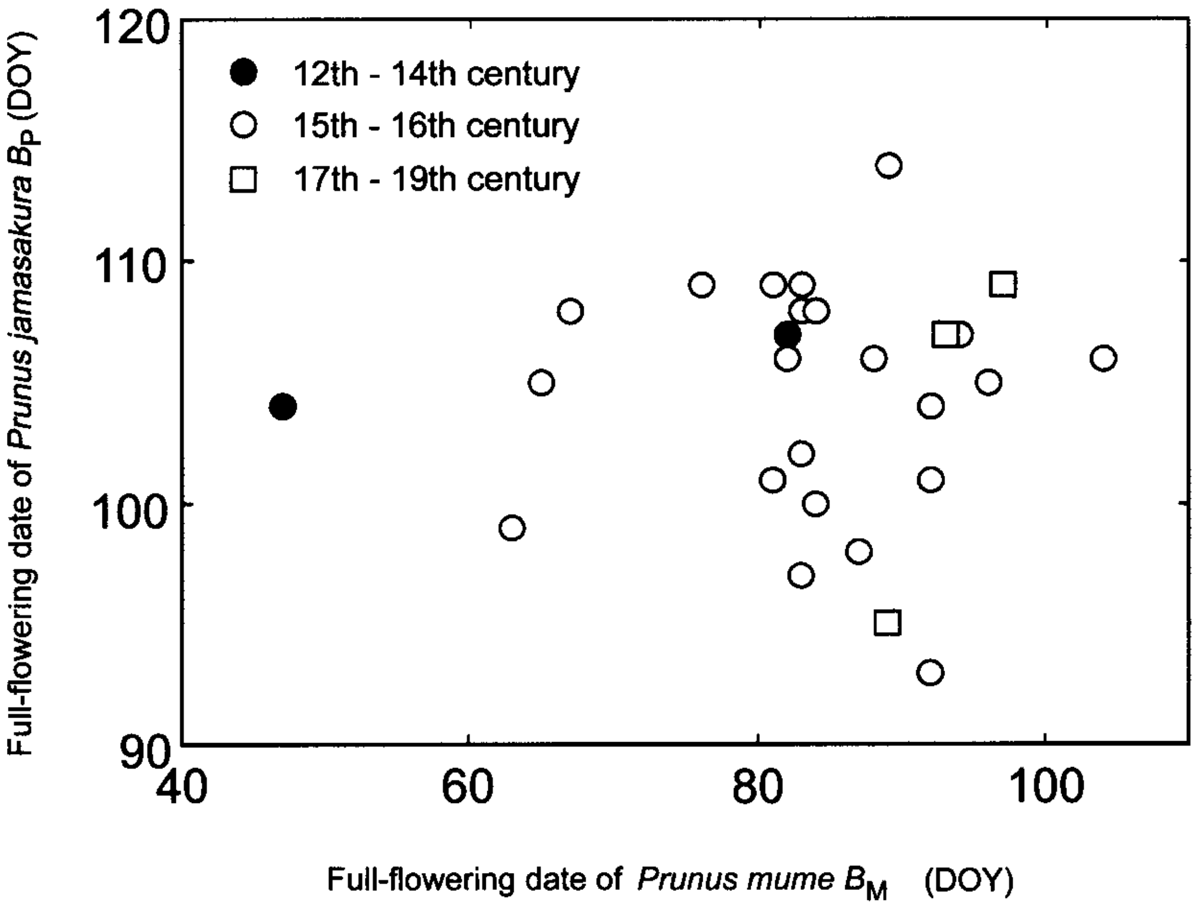



$B_P = 0.57\ B_W + 29.46\quad (r^2 = 0.53)$
12th - 14th century
15th - 16th century
17th - 19th century
20th - 21st century
Full-flowering date of *Prunus jamasakura* B_P (DOY)
Full-flowering date of *Wisteria floribunda* B_W (DOY)
110
100
90
100
110
120
130
140

Aono and Saito, Figure 4



Aono and Saito, Figure 5



Aono and Saito, Figure 6