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INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **28**: 905–914 (2008)
Published online 1 August 2007 in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/joc.1594

Phenological data series of cherry tree flowering in Kyoto, Japan, and its application to reconstruction of springtime temperatures since the 9th century

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ABSTRACT: Changes in springtime temperature in Kyoto, Japan, since the 9th century were reconstructed, using the phenological data series for cherry tree (*Prunus jamasakura*), deduced from old diaries and chronicles. Phenological data for 732 years was made available by combining data from previous studies. The full-flowering date of cherry trees fluctuates in accordance with temperature conditions during February and March. Full-flowering dates were closely related to the March mean temperature by means of a temperature accumulation index, in which plant growth is considered to be an exponential function of temperature. Calibration enabled accurate estimation of temperatures in the instrumental period, after 1880; the root mean square error (RMSE) of temperature estimates was determined to be within 0.1 °C, after smoothing by local linear regression over time spans of 31 years. The results suggested the existence of four cold periods, 1330–1350, 1520–1550, 1670–1700, and 1825–1830, during which periods the estimated March mean temperature was 4–5 °C, about 3–4 °C lower than the present normal temperature. These cold periods coincided with the less extreme periods, known as the Wolf, Spoerer, Maunder, and Dalton minima, in the long-term solar variation cycle, which has a periodicity of 150–250 years. The sunspot cycle length, a short-term solar variation cycle, was also compared with the temperature estimates, with the result that a time lag of about 15 years was detected in the climatic temperature response to short-term solar variation. Copyright © 2007 Royal Meteorological Society

KEY WORDS climatic reconstruction; old documents; Kyoto; phenology; cherry blossom; springtime temperature; solar variation

Received 23 August 2006; Revised 17 May 2007; Accepted 10 June 2007

1. Introduction

As plants reach the various developmental stages of their annual life cycle, phenological events, such as leafing, flowering, and fruiting, occur. The timing of a phenological event fluctuates under the influence of integrated climatic conditions during the period of growth and development. The plant phenological events in springtime under temperate climate occur, when the integrated climatic conditions, mainly temperature, are satisfactory. Therefore, the timing of a plant phenological event often provides information for estimating geographic climatic variation on a local scale (Kalb, 1962).

Phenological data series of plants can be used as a proxy for climate change if the seasonal timing of a phenological event can be closely related to specific climatic conditions during plant development. Many studies have reconstructed historical climate changes by combining different types of proxy such as data from tree rings, sediments, and ice cores (e.g. Jones *et al.*, 1998; Mann *et al.*, 1999). Such climatic reconstruction requires that the proxy data be calibrated using known climatic conditions and the proxy record must also be dated. Although phenological data series, acquired from historical records, enable climatic reconstruction on a shorter time scale than other proxies, the phenological data are accompanied by concrete dates, allowing precise reconstruction without requiring the use of an external dating procedure.

In England, phenological events of various plants and animals observed since the 18th century have been reported as Marsham's phenological data series (Margary, 1926). Sparks and Carey (1995) related various phenological data to meteorological factors and predicted changes in the future timing of each phenological event, using the climatic scenario IS 92. In Geneva, Switzerland, the leafing date of the chestnut tree has been observed since 1808, and these records have been used to show climatic warming since the early 19th century (Lauscher and Lauscher, 1981).

In Japan, the flowering of the cherry tree is the most commonly observed phenological event. Flowering is generally observed from late March to mid-April in western and central Japan, and shows inter-annual variation within a range of approximately 3 weeks at a given location. The inter-annual variation in the flowering time of the cherry tree depends closely on the general temperature conditions during the development of the

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flower buds in February and March (Aono and Omoto, 1990, 1993, 1994; Aono, 1998).

In Japan, routine phenological observations at weather stations started only about 100 years ago. However, at Kyoto, which was the capital of Japan from A.D. 794 to 1868, Taguchi (1939) found old descriptions on the flowering of the cherry trees in many diaries and chronicles, covering the total of about 100 years scattered between 812 and 1864. Arakawa (1956) considered these data to be a proxy for the full-flowering date of the cherry tree and discussed their utilization for historical climatic reconstruction. Sekiguchi (1969) added data for an additional 20 years and outlined climate change over a long time scale from 8th to 19th centuries by using the averaged full-flowering date for each century. Lauscher (1978) presented the data series of Kyoto, developed in earlier studies, in detail.

Aono and Omoto (1993) obtained full-flowering dates for the other 136 years scattered between 10th and 19th centuries from further investigation of additional old diaries and chronicles and added them to the previously compiled data series to fill gaps in previous data series. They used the newly compiled series to deduce changes in the March mean temperature at Kyoto since the 14th century. Aono and Omoto (1994) also obtained flowering data for another 223 years to fill gaps in the phenological data series compiled by earlier studies. Although the temperature estimates that we reported in previous studies (Aono and Omoto, 1993, 1994) suggested that cold conditions prevailed in the early 14th century and the middle of the 16th century, continuous and accurate estimates could not be deduced for the 17th–19th centuries, because very little phenological data were available.

In this study, we attempted to deduce changes in the March mean temperature at Kyoto since the 9th century on the basis of phenological data on cherry tree flowering. To obtain sequential temperature estimates, we collected large numbers of phenological descriptions from old diaries and chronicles, and from previous studies, and applied them to climatic reconstruction. We applied a temperature accumulation model that uses the number of days transformed to standard temperature (DTS) as an index (Aono and Omoto, 1990; Aono, 1998; Honjo *et al*., 2006); first to calibrate the relationship between the March mean temperature and cherry tree phenological data using data after 1880, and then to estimate the March mean temperature for the earlier historical period. Then we compared the reconstructed March mean temperature series with the solar variation cycles and investigated the climatic response as reflected by the reconstructed temperature change at Kyoto to changes in solar activity.

2. Phenological data series in the historical period

2.1. Investigation of phenological information

In this study, we investigated phenological data on the flowering of the cherry tree at Kyoto from A.D. 801 to 2005. We divided the whole research period into two subsections, the historical period (A.D. 801–1880) and the instrumental period (A.D. 1881–2005), because modern meteorological observation started at Kyoto in 1881. Phenological data from the instrumental period were calibrated using springtime temperature observations, and then data from the historical period were used to reconstruct climate changes.

The urbanized area of Kyoto (35°00′N, 135°40′E) is located in a basin surrounded by mountains (300–500 m), except on the south (Figure 1). The two imperial palaces were constructed in this city centre at different times. The western (older) palace was depleted and only the east one was relevant. Many old diaries record people's observations of cherry blossoms at many places in the city and on the slopes of the surrounding mountains.

For the historical period, we investigated old diaries and chronicles written at Kyoto to obtain phenological data on cherry tree flowering. Because Kyoto was the capital of Japan from 794 to 1868, many diaries, written by emperors, aristocrats, politicians, monks, and merchants, dating to that period have been preserved at Kyoto.

First, we determined the species of the most common cherry tree at Kyoto during the historical period. In the modern phenological observations by the Japan Meteorological Agency, *Prunus yedoensis* (Japanese common name, Somei–Yoshino) is considered representative of all cherry trees, and its full-flowering dates are observed by most meteorological stations in Japan, except those in Hokkaido District and the Ryukyu Islands. However, *P. yedoensis* is an ornamental tree developed in the middle of the 19th century, and it did not exist before that. Many descriptions in old documents suggest that a native species, *Prunus jamasakura* (Japanese common name, Yamazakura), was grown in Kyoto and its suburbs, and it was planted also in the ground of the imperial palace from ancient times. Therefore, *P. jamasakura* was the most common species of cherry tree in Kyoto until the middle of 19th century.

In modern times, cherry-blossom viewing parties are generally held under full-flower status. Many descriptions in the old diaries suggest that even in the historical period, cherry-blossom viewing parties were held when the cherry trees were full with flowers. Trees of *P. jamasakura* generally show their full-flower status only for 2–4 days period, shorter than those of other cherry tree species. Many records also suggested that the onset of full-flower status strongly brought about the motives for dwellers in Kyoto immediately to hold the parties and sightseeing for the purpose of viewing cherry blossoms. Therefore, the date, on which the event with cherry-blossom viewing was performed, seems to be considerably near to the first date in full-flower status.

Thus, historical descriptions found in old documents can be used as phenological data for the full-flowering date of the cherry tree. In this study, the dates, according to the Japanese lunar calendar, on which cherry-blossom viewing parties were held or on which the trees were

DOI: 10.1002/joc

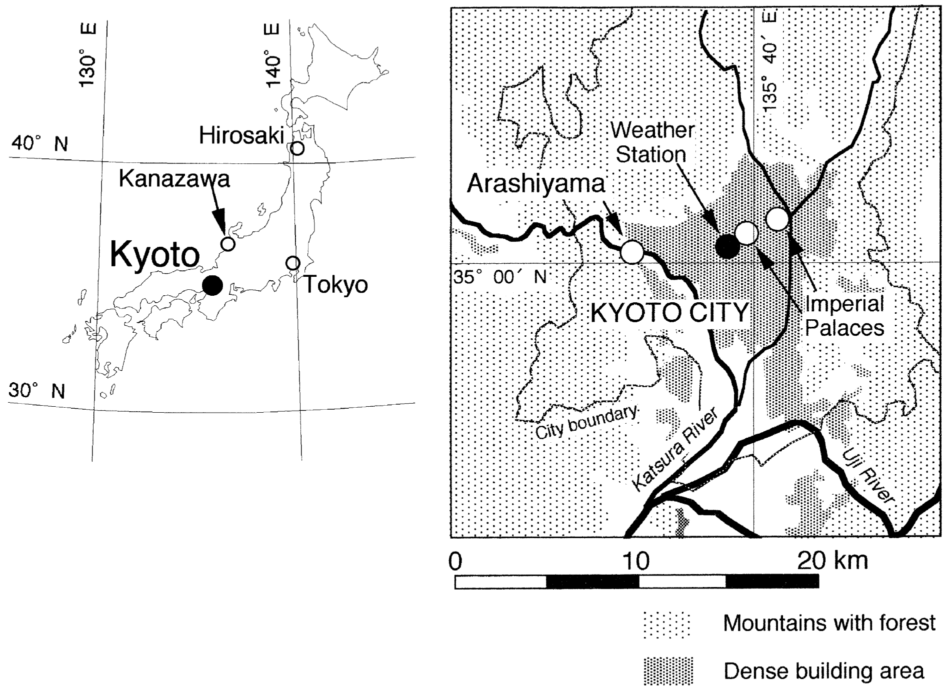

Figure 1. Map of the Kyoto area, and locations of Kyoto and Kanazawa in Japan.

observed to be full with flowers were compiled and then converted to the day of year (DOY) according the modern Gregorian calendar. We regarded these dates as the first dates in full-flowering status, or the full-flowering dates, of *P. jamasakura.*

To relate phenological data to springtime temperature, we needed to collect full-flowering dates for the period after modern meteorological observation started in 1881. The full flowering of *P. jamasakura* is not routinely recorded at meteorological stations. However, Arashiyama, a western suburb of Kyoto is a famous sightseeing point for viewing the flowering of *P. jamasakura,* even at present. Therefore, we were able to collect the necessary phenological information on *P. jamasakura* from daily newspapers up to 2005, in which railway companies frequently reported the flowering status in advertisements for visitors who might visit Arashiyama. In this study, phenological data from the historical and instrumental periods were combined into a single data series of the full-flowering dates of *P. jamasakura* at Kyoto.

2.2. Phenological data series for cherry tree flowering

Including the data collected for our previous studies (Aono and Omoto, 1993, 1994), we acquired full-flowering dates for 601 years: 386 dates from old diaries, 87 from chronicles, 17 from Japanese poetry, and the rest from advertisements in daily newspapers, for a total of 732 data points, including those compiled by earlier studies and with some substitutions made after considering the validity of various recorded descriptions. Finally, we had available for use full-flowering data for 60.7% of the years in the whole research period (A.D. 801–2005).

The full-flowering dates collected from old documents and newspapers show considerable inter-annual variation (Figure 2). The data for earlier periods include large gaps, because many old records were missing as a result of natural disasters or conflagrations. Although phenological data were available only for 7 years in the 9th century, the number of data points increased over time. An almost complete sequential data series was obtained from the 15th century onward: data were available for more than 80% of the years for the period from 1401 to 2005. However, large gaps of 3–10 years duration in the phenological data series occurred even after the 15th century because of political and social unrest (e.g. the Ohnin Civil War, A.D. 1467–1477, and the Meiji Restoration, A.D. 1868). Even in the 20th century, no phenological data were available from 1942 to 1945, the period of World War II.

The earliest full flowering occurred on DOY 86 (27 March) in 1409, and the most delayed event occurred on DOY 128 (8 May) in 1526. The average full-flowering date over the whole research period was DOY 105 (15 April), which is 7 days later than what is normal at present, averaged over the period 1971–2000 (DOY 98, 8 April). Flowering frequently occurred relatively late, from DOY 110 (20 April) to DOY 120 (30 April), during three periods: the early 13th century, the mid-15th century and the late 17th century. Secular changes in the full-flowering date showed an apparent repeating pattern with a long cycle length of approximately 200 years (Figure 2).

The amount of variability in the fluctuation of the full-flowering date differed among centuries (Table I). Full-flowering dates in the 20th–21st centuries have a standard deviation of 5.0 days, which is 1.0–2.3 days smaller than the standard deviation in other centuries. The larger fluctuation in full-flowering dates before the 20th

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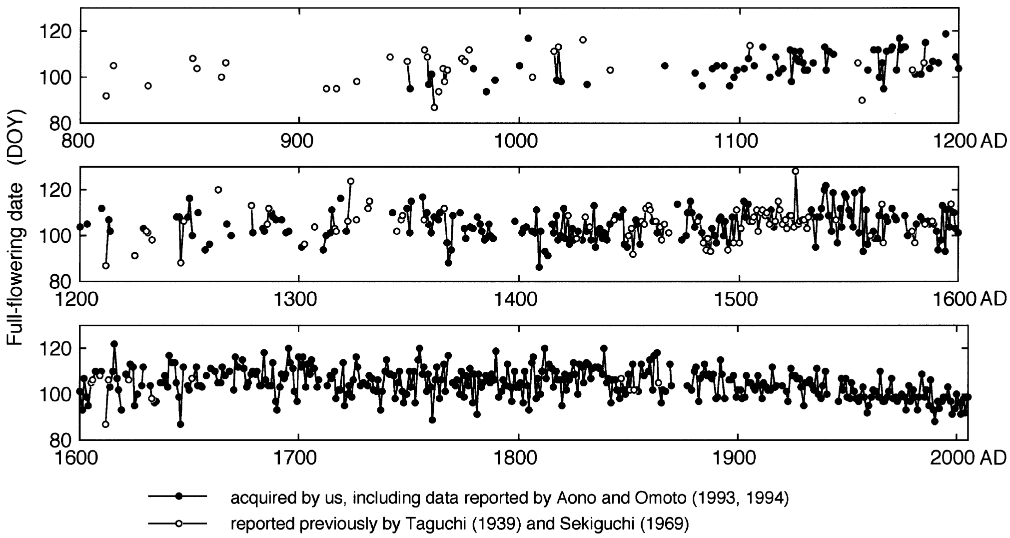

Figure 2. Inter-annual variation of the full-flowering dates of the cherry tree, *P. Jamasakura*, at Kyoto, acquired from old diaries and chronicles.

Table I. Statistics of full-flowering date for each century.

Century	Number of data	Averages (DOY)	Standard deviation (days)
9	7	102	5.8
10	22	102	6.8
11	18	104	6.5
12	50	107	5.7
13	35	104	7.3
14	50	105	6.8
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	5.0
Whole period	732	105	6.5
Historical period	614	105	6.5
Instrumental period	118	102	5.3

century was apparently caused by the large subjectivity with which the different individuals who wrote the diaries viewed the cherry tree flowering status, as well as by the different geographical points at which this phenological event was observed.

3. Calibration of phenological data to springtime temperature

3.1. Estimation of full-flowering dates during the instrumental period

To relate changes in the full-flowering dates to changes in springtime temperature, we used the DTS model, which proposes exponential contribution of temperature to the development of trees. The DTS model has been applied to the nation wide prediction of the flowering dates of cherry trees by the Japan Meteorological Agency since 1996. In the estimation of flowering dates for cherry trees, the accuracy given by DTS model is generally higher than that given by some other common approaches, such as the growing-degree days. In our preliminary estimation of the full-flowering dates in 20th century, it was verified that the root mean square error (RMSE) in DTS model was generally 0.4 days smaller than that in the growing-degree-day approach.

In this study, we attempted to tune-up the DTS model with a process to estimate the full-flowering dates at Kyoto for 1901–2005 with high accuracy. We used the daily mean temperature observed at the Kyoto Meteorological Observatory for this process. DTS, proposed by Konno and Sugihara, 1986) is calculated from the daily mean temperature. The daily DTS value is a ratio expressing the amount of growth that occurs in one day at the actual daily mean temperature with respect to that which occurs at the temperature set as a standard. The DTS value on the jth day of the ith year is calculated as follows:

$$(t_s)_{ij} = \exp\left\{\frac{E_a(T_{ij} - T_s)}{R \cdot T_{ij} \cdot T_s}\right\} \quad (1)$$

where T_{ij} is the daily mean temperature on the jth day of the ith year, T_s is the standard temperature (288.2 K, somewhat higher than flowering-time temperature, was used in this study), 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 the variable expressing the responsiveness of flower bud development to temperature. The estimated full-flowering date is the day when the cumulative DTS value reaches a predetermined mean value, DTS_{30}, which is calculated as follows:

$$DTS_{30} = \frac{1}{N}\sum_{i=1}^{N}\sum_{j=D}^{B_i}(t_s)_{ij} \quad (2)$$

where N is the number of years used for calibration, D is the day on which accumulation starts (hereafter, the starting date), and B_i is the full-flowering date in the ith year.

In this study, the value of N was set to 30, which we considered an appropriate number of years to be representative of the normal climatic condition. Therefore, we used the data set of temperature and full flowering from only 30 years to calibrate the DTS model, and the remainder of the instrumental period was used for verification of the accuracy of the full-flowering date estimates. We selected the period from 1911 to 1940 for the calibration, to minimize the effect of both missing phenological data and recent urban warming on estimates in the calibration period. For accurate estimation, suitable values for the starting date, D, and the temperature characteristic, E_a, must be determined. The suitable value of starting date, D, roughly corresponds to the date when the endodormancy of cherry tree flower buds completes. In this study, we determined the most suitable values for D and E_a by an error analysis over the 30-year calibration period. In this error analysis, we calculated the RMSE for each combination of D (at 1-day intervals) and E_a (at intervals of 4 kJ mol^{-1}) in the estimation of full-flowering dates for the period from 1911 to 1940, and the combination of values resulting in the smallest error was considered the most suitable basis for estimation. From the error analysis, DOY 42 (11 February) for D and 56 kJ mol^{-1} for E_a were determined as the most suitable values. We verified the validity of these values by using them to estimate the full-flowering dates over the longer period, from 1901 to 2005.

Comparison of the full-flowering dates estimated using these values with the actual dates for 1901–2005 (Figure 3) showed that the estimated changes in the full-flowering date agreed well with actual changes, not only for the calibration period but also for the whole verification period. The RMSE of estimates for the whole period was 2.5 days, while that over the calibration period was 2.4 days, suggesting that the suitable combination of D and E_a values is applicable to the estimation of full-flowering dates for periods other than the calibration period.

3.2. Estimation of March mean temperature in the instrumental period

March mean temperature was estimated by inverse application of the DTS method. To estimate temperature, the normal DTS accumulation, DTS_N, was calculated using the daily mean temperatures and mean full-flowering date which was averaged over the calibration period (1911–1940). In our previous studies (Aono and Omoto, 1993, 1994), DTS_N was calculated as follows:

$$DTS_N = \sum_{j=D}^{B_N-1} \exp\left\{\frac{E_a(T_{Nj} - T_s)}{R \cdot T_{Nj} \cdot T_s}\right\} + 0.5 \exp\left\{\frac{E_a(T_{N(B_N)} - T_s)}{R \cdot T_{N(B_N)} \cdot T_s}\right\} \quad (3)$$

where B_N is the average full-flowering date over the calibration period, T_{Nj} is the normal daily mean temperature on the jth day, and $T_{N(BN)}$ is the T_{Nj} value on B_N. These normal values were derived from averages over the period 1911–1940. Furthermore, a constant temperature anomaly was added to the normal daily temperature values. This anomaly was adjusted so that the DTS value accumulated until the actual full-flowering date in each year agreed with DTS_N. For the ith year, in which full flowering was observed on B_i, the estimated temperature anomaly, ΔT_i, was derived as follows:

$$\sum_{j=D}^{B_i} \exp\left\{\frac{E_a(T_{Nj} + \Delta T_i - T_s)}{R \cdot T_s \cdot (T_{Nj} + \Delta T_i)}\right\} \approx DTS_N \quad (4)$$

In Equations (3) and (4), the combination of values determined as described above, DOY 42 for the starting date, D, and 56 kJ mol^{-1} for the temperature characteristic, E_a, was used. The sum of the March mean temperature averaged over 1911–1940 (6.4 °C) and the derived temperature anomaly, ΔT_i, was regarded as the estimated March mean temperature for the ith year.

The March mean temperature estimates for the whole instrumental period of 1881–2005 were compared with the actual values to verify the accuracy of the method (Figure 4). The estimated temperatures for the calibration period (1911–1940) showed a large RMSE of 0.8 °C, and those for the verification period (1881–1910 and

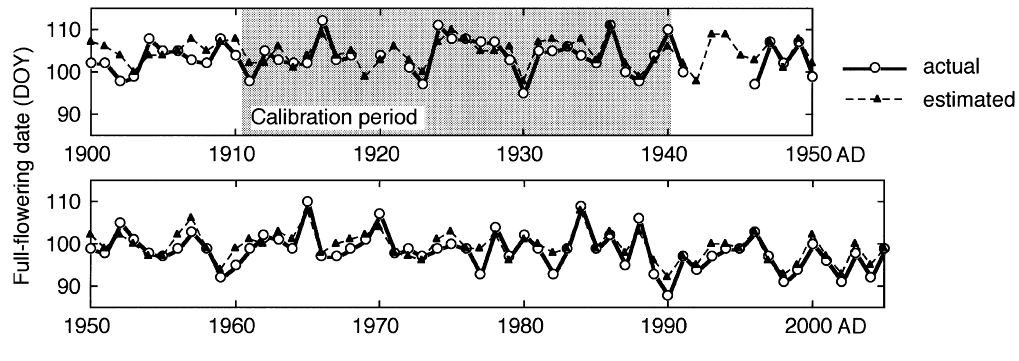

Figure 3. Actual and estimated full-flowering dates of the cherry tree, *P. jamasakura*. Dates were estimated by using suitable values for the variables D and E_a in the DTS model.

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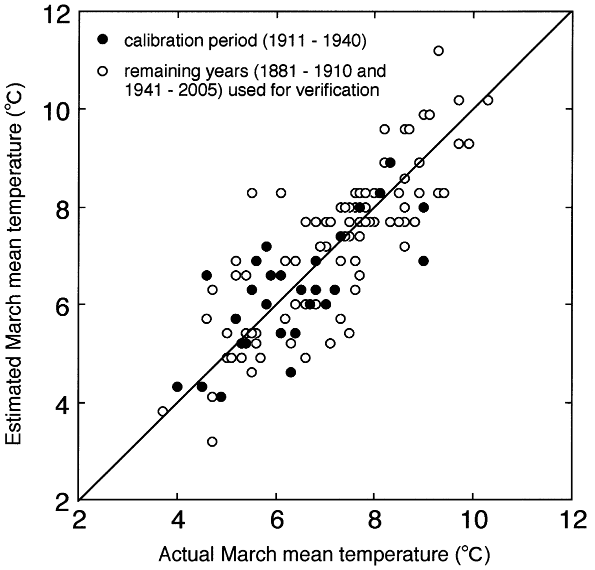

Figure 4. Comparison of estimated March mean temperatures with actual temperatures for each year. In this scatter diagram, the solid circles indicate the results for the calibration period and the open circles indicate those for the remaining years, used for verification.

1941–2005) had an RMSE of 0.9 °C. However, these errors appear on both sides of the normal line (Figure 4), regardless of whether the actual temperatures were higher or lower. The simple mean of the error over both the calibration and verification periods was 0.0 °C, indicating that the temperature estimates had no bias with respect to actual temperature values in either period.

Therefore, application of a smoothing procedure to the time series to cancel the errors in the yearly estimates could be expected to yield temperature estimates with relatively high accuracy. For the historical period, the moving average method is not an appropriate smoothing procedure because a large data gap in either the first or second half of the time span used for the moving average would give rise to a large bias in the smoothed series. Therefore, we tested local linear regression as a smoothing procedure. We compared secular changes in the actual temperatures with estimated temperatures after smoothing by local linear regression over 31-year spans (Figure 5). For the whole instrumental period, the smoothed estimated temperature changes fitted well to the actual temperature changes, with a RMSE of only 0.1 °C. Even during the most recent 50 years, when significant urban warming occurred at Kyoto, the estimates matched the actual temperature closely. These results suggested that the magnitude of urban warming at the meteorological observatory and at Arashiyama, where the full flowering was observed during instrumental period, was similar, indicating that the temperature estimates from the phenological data were affected by urban warming during the most recent 50 years.

4. Estimation of March mean temperature in the historical period

We estimated the March mean temperature in the historical period using the same procedure as that used for the estimation in the instrumental period. The estimates are expressed as a curve smoothed by local linear regression over 31-year spans. We used a fixed time span of 31 years regardless of the number of phenological data points.

The secular changes in estimated March mean temperature at Kyoto since the 9th century are shown in Figure 6. The more full-flowering dates lie within the span for the local regression, the more accurate are the temperature estimates (Aono and Omoto, 1993, 1994). Thus, the curves expressing secular change are drawn with different thicknesses to indicate differences in the number of data points in each 31-year span used during smoothing. Smoothing was not performed when there was no phenological data in either the first or second 15 years of a 31-year span to avoid having the smoothed value become an extrapolation. In order to examine the accuracy of smoothed value, the 95% confidence intervals on the smoothed value by the local linear regression for each time span are also depicted in dotted lines. The smaller number of data points in the time span used for smoothing by local linear regression gives the wider width of confidence interval, which implies more uncertainty of smoothed temperature.

In the earlier period, from the 9th to 11th century, no clear changes in temperature could be deduced, except for a short-term decline in temperature from 950 to 1020. In the 12th century, for which full-flowering dates for about 50 years were available, the estimated temperature fluctuated around 6 °C. The reconstructed temperature was relatively lower throughout the 12th century, and a rising trend was recorded from 1200 to 1230. The relatively low temperatures in the 12th century estimated in this analysis contrast with those deduced by Yamamoto (1967), who showed that the winter temperature rose significantly at Kyoto during the 12th century. These

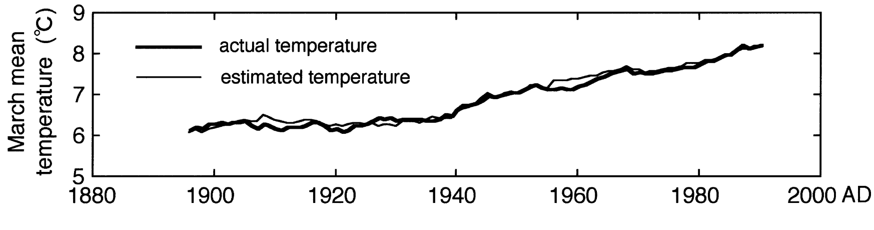

Figure 5. Actual and estimated March mean temperatures during the instrumental period, smoothed by the local linear regression procedure using a 31-year time span.

DOI: 10.1002/joc

contrasting results can be explained by the different seasons used for reconstructing climate change between the studies. After the warming trend from 1200 to 1230, a long-term cooling trend was recorded from 1230 to 1330. The estimated temperatures for 1330–1350 were 4–5 °C, the lowest temperature estimates in this study.

After the decline in temperature recorded in the 14th century, the estimated temperatures began to have higher accuracies than before, because the number of phenological data points in each 31-year span used for smoothing become larger than 22 (70% of years). Such large number of data points in 31-year time span made smoothed temperature more certain. In almost whole period since 1400, the width of the 95% confidence interval was narrower than 2.0 °C (±1.0 °C for both sides of the smoothed value). A clear warming trend from 1350 to 1400 and a cooling trend from 1430 to 1540 were recognized (Figure 6). Conditions during 1520–1550 were cold, in agreement with low reconstructed winter temperatures at Kyoto during the 1520s, deduced from daily weather descriptions in old diaries (Yamamoto, 1971).

In the 17th and 18th centuries, temperature changes showed three distinctive features: a cooling trend from 1600 to 1670, a warming trend from 1700 to 1720, and almost constant temperatures of around 6 °C from 1720 to 1800. From 1670 to 1700, estimated temperatures were particularly low; around 5 °C. In agreement with this finding, Maejima and Tagami (1983) determined from changes in the number of days with snowfall at Hirosaki city in Aomori, Japan that relatively cold springs characterized the period from the end of the 17th to the beginning of the 18th century.

The most distinctive feature of the estimated temperature changes after the 18th century is a period of relative coldness from 1825 to 1830. In particular, in 1826 the estimated temperature was 4.9 °C, the lowest in the past 200 years. In magnitude, this cold period was similar to that at the end of 17th century. A short-term cold period in the 1820s has also been reported by Maejima and Tagami (1983) and Kawamura (1992).

The secular changes in temperature during the historical period deduced in the present study show some similarities with those indicated by climatic proxies in other countries. In a millennium-scale Northern Hemisphere temperature reconstruction, Mann *et al.* (1999) reported cold periods in the 14th and 17th centuries that apparently coincide with cold periods deduced in this study, but others in the 15th and 16th centuries had no matches in our results. In Asia, a climatic proxy data series from the Guliya ice cap on the Tibetan Plateau (Thompson *et al.*, 2003), which is almost at the same latitude as Kyoto, shows a pattern of secular changes very similar to that in our study, which may be noteworthy, although the exact timing of the temperature minima differs. A comparison of our result with temperature estimates of the winter half-year in eastern China (Ge *et al.*, 2003) also shows some coincidence between cold periods during the past 300 years. However, temperature reconstructions for the warm season (May–August) in Beijing, China (Tan *et al.*, 2003), did not show changes similar to those in our study. These comparisons suggest that changes in the March mean temperature estimated in this study show more similarity to general winter temperature changes in eastern Asia than to summer temperature changes.

In this study, estimated temperature generally shows a rising trend after the 1820s, which continues until the present. Both the actual and estimated temperatures in 1990 were, respectively 8.2 and 3.3 °C higher than the

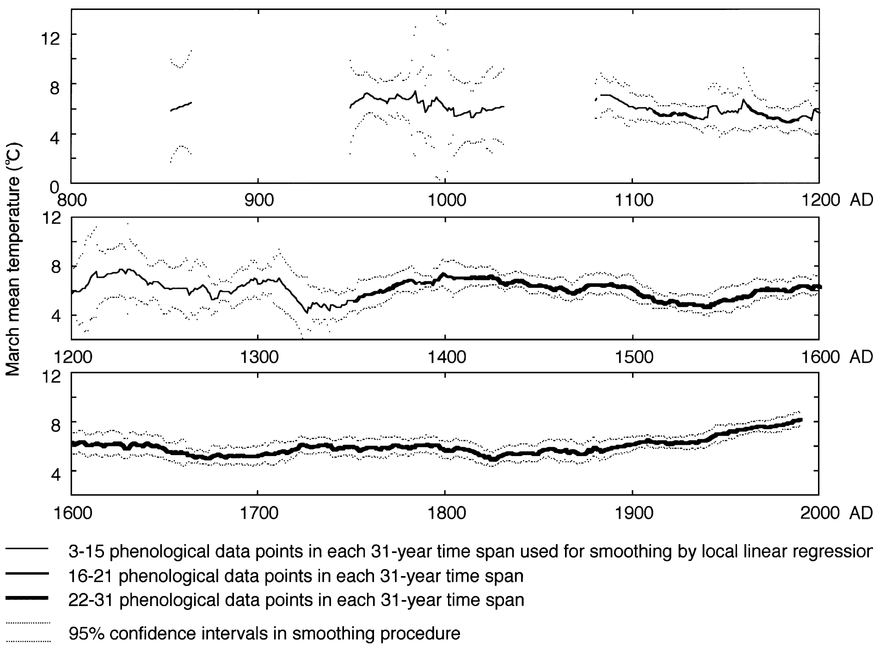

Figure 6. March mean temperature reconstruction at Kyoto in the historical period, since the 9th century. Different curve thicknesses indicate differences in the number of phenological data points in each 31-year span used by the local linear regression procedure. Confidence intervals (95%) on the smoothed value are also shown in dotted lines.

DOI: 10.1002/joc

estimate of 4.9 °C in 1826. Kawamura (1992) reconstructed March mean temperatures in Kanazawa, Japan, using phenological data on cherry tree flowering and concluded that a 2.5 °C temperature rise occurred from the 1820s to the present. Urban warming, which is significant in a large city such as Kyoto, may explain the difference in the temperature rise between Kyoto and Kanazawa. The 31-year moving average of urban warming bias in the March mean temperature calculated by the method of Omoto and Hamotani (1979) and Omoto and Aono (1990/1991) showed a rapid increase of 1.1 °C from 1940 to 1990, suggesting that 2.2 °C, estimated by subtracting the urban warming bias of 1.1 °C from the estimated temperature rise since 1826 at Kyoto, represents the amount of regional-scale climatic warming in western and central Japan since the early 19th century.

5. Estimated temperature change and the solar cycle

5.1. Comparison with changes in long-term solar variation

Solar variation, which we consider as one of the main factors affecting the global climate change in the historical period, was compared with the estimated March mean temperature changes at Kyoto. Solar variation is generally regarded as a cause of not only tropospheric solar forcing but also stratospheric heating and the modification of stratospheric and tropospheric wind systems (Kodera and Kuroda, 2002; Kodera, 2004).

Therefore, we compared the estimated March mean temperature changes in relation to long-term solar variation over the past centuries (Figure 7). Changes at Kyoto since the 9th century were compared with changes in the number of sunspots as reconstructed by Solanki *et al.* (2004; Figure 7). Periods of less extreme solar variation (shaded sections in Figure 7) occurring at intervals of 150–250 years are generally known as the Oort (1010–1050), Wolf (1280–1340), Spoerer (1420–1570), Maunder (1645–1715), and Dalton (1790–1820) minima. In general, synchronicity of the reconstructed cold periods with solar minima was verified, but because our temperature estimates could not show continuous change until 1100, the temperature decline corresponding to the Oort minimum was not detectable. Higher solar activity characterized the 12th century; nevertheless, the temperature estimates were low (5–6 °C). Since the number of 12th century full-flowering data points exceeded 50, we consider the temperature estimates for this period to be relatively accurate. The reason for the discrepancy between the change in solar activity and that in the estimated temperature during the 12th century is unclear.

Around the end of the Wolf minimum (1280–1340), the estimated temperature change curve shows a low minimum (Figure 7). In the 1340s, the estimated temperatures were 4–5 °C. During the Spoerer minimum (1420–1570), estimated temperatures again declined. The lowest estimated temperature value of 4.7 °C occurred in 1538, near the end of the period of low solar activity, and was followed by a rising trend in estimated temperature until the end of 16th century. The estimated change in temperature during the Maunder minimum (1645–1715) paralleled that in the reconstructed series of sunspot number, reported by Solanki *et al.* (2004). The minimum estimated temperature during this period was 5.0 °C in 1673, which is almost the same as the minimum temperature estimate during the Spoerer minimum. Also, from 1790 to 1820, corresponding to the Dalton minimum, a short period of less extreme solar variation, a decline in the estimated temperature was recognized. The minimum estimated temperature of 4.9 °C was obtained in 1826, just after the end of the Dalton minimum.

Some cold periods during which the March mean temperature was 4–5 °C thus correspond to the less extreme periods in the long-term solar variation cycle. The lowest temperature estimates occurred in the second half of the Wolf and Spoerer minima and just after the end of the Dalton minimum, suggesting some time lag in the change in springtime temperatures at Kyoto with respect to the long-term solar variation cycle.

5.2. Comparison with the 11-year sunspot cycle

The temperature estimates after the 1750s were also compared with short-term solar variation, with a cycle length of about 11 years, known as the Schwabe cycle. The sunspot cycle does not follow the periodicity of 11 years exactly; instead, the length of the sunspot cycle becomes shorter during more active phases of solar variation. Friis-Christensen and Lassen (1991) compared the length of a sunspot cycle with annual temperatures in the Northern

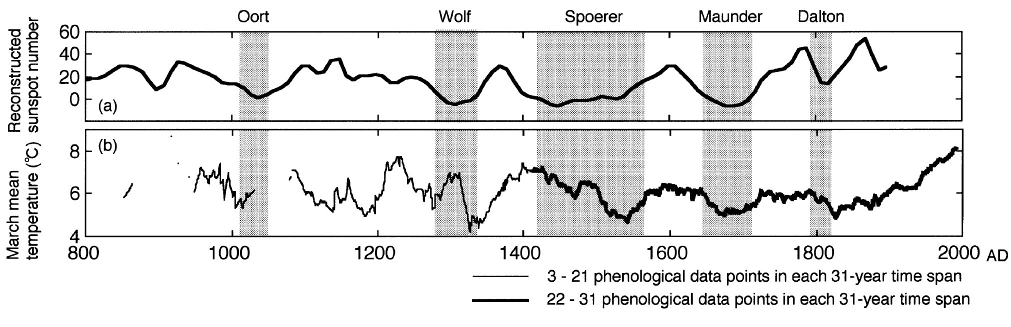

Figure 7. (a) Reconstructed sunspot number (Solanki *et al.*, 2004) and (b) temperature reconstruction smoothed by local linear regression procedure over a time span of 31 years. The shaded intervals indicate periods of less extreme solar variation.

DOI: 10.1002/joc

Hemisphere and found that changes in both were simultaneous. Hence, in this study, we compared the temperature estimates with the cycle length from one sunspot peak to the following peak. The 13-month moving average of the monthly sunspot number by the Belgium Royal Observatory (Van der Linden and the SIDC team) was used in this analysis. We used 10-, 15-, and 20-year block means of the annual temperature estimates at Kyoto without applying the smoothing procedure to determine the relationship to the sunspot cycle length. To acquire the actual relationship between temperature estimates and the length of the sunspot cycle, it was necessary to eliminate the influence of urban warming at Kyoto, which was done for the recent 50-year period by using the method proposed by Omoto and Hamotani (1979), and Omoto and Aono (1990/1991).

When temperature estimates were averaged over 10-year intervals ending at the same time as the end of the corresponding sunspot cycle, each averaging interval overlapped almost exactly the interval between sunspot number peaks (Figure 8(a)). However, the pattern of temperature changes did not match that of the sunspot cycle. Especially in the first half of the 19th century, shorter sunspot cycles were followed by periods with higher temperature estimates. Therefore, we compared sunspot cycle length with estimated temperature averages over intervals lagging the corresponding solar cycle.

First, we compared the solar cycle length with the temperature averaged over 10-year periods beginning at the end of the corresponding sunspot cycle, with the result that the patterns of changes were considerably similar between the averaged temperatures and sunspot cycle length (Figure 8(b)). Especially in the 19th century, higher temperatures corresponded to sunspot cycles of shorter length. Moreover, when the averaging period was extended to 15 years, using the same starting year, the two patterns became even more similar (Figure 8(c)). Before the 20th century, when the solar activity had greater influence on temperature than other possible factors such as greenhouse gases, the temperature estimates averaged over the 10-year period beginning after the start of the sunspot cycle correlated with the length of the solar cycle in the historical period ($r^2 = 0.37$). Moreover, with 15-year averaged temperatures, somewhat high correlation ($r^2 = 0.57$) with the solar cycle length in the historical period was obtained. The correlation of the 20-year averaged temperature with the corresponding solar cycle, however, was lower ($r^2 = 0.25$).

These results showed that the secular change in springtime temperature at Kyoto lagged the short-term solar variation by about 15 years. Waple *et al.* (2002) conducted a correlation analysis of reconstructed surface temperature proxies and solar activity on a global scale and found that in eastern Asia, including Japan, Southeast Asia, South Asia, and the northern territory of Australia, the correlation between surface temperature and solar activity was higher if a delay of 14 years in the climatic response was used. Shindell *et al.* (2001) also reported a delay of about 20 years in the climatic response in eastern Asia to solar variation. Thus, the delay in the climatic response of the March mean temperature deduced from phenological information was similar to delays suggested by previous researchers. It is interesting that a time lag in climatic response was detected even in the temperature reconstructions for the specific month of March at a specific point of Kyoto.

6. Concluding remarks

The phenological data on the full flowering of the cherry tree acquired from many diaries and chronicles written at Kyoto constitute an useful proxy for climatic

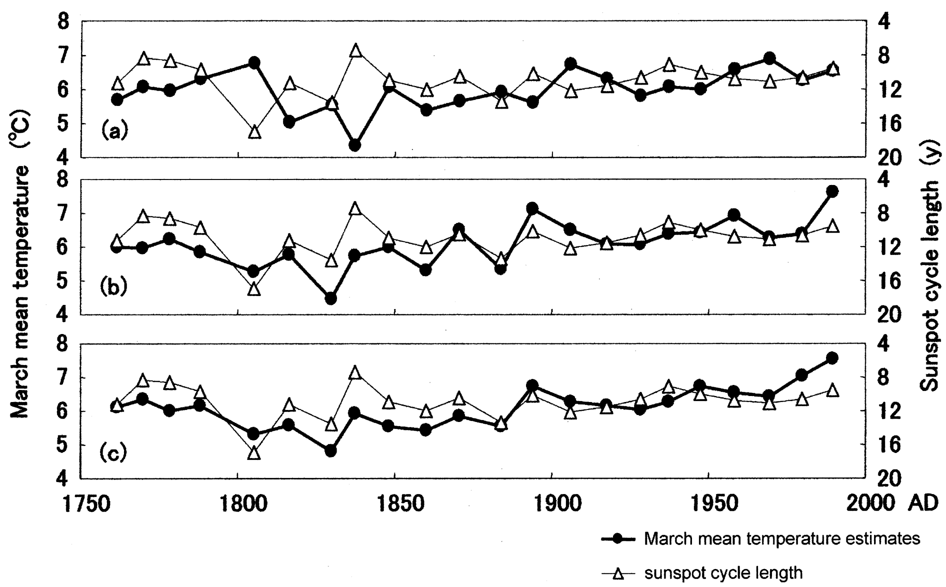

Figure 8. Comparison of sunspot cycle length with temperatures averaged over different periods: (a) averaged over a 10-year period ending at the same time as the end of the corresponding sunspot cycle; (b) averaged over a 10-year period beginning at the end of the corresponding sunspot cycle; (c) averaged over a 15-year period beginning at the end of the corresponding sunspot cycle.

DOI: 10.1002/joc

reconstruction in the historical period, because of the length and continuity of the data series and the close relationship with springtime temperature. Phenological data was acquired for a total of 732 years, covering over 70% of years since the middle of 13th century and over half of the total number of years in the study period. To substantially complete the data series before the middle of 13th century, it will be necessary to investigate additional old documents.

The calibration and verification of March mean temperatures deduced from the phenological data in the instrumental period showed high accuracy (RMSE within 0.1 °C) for estimation on the basis of normal climatic conditions, when smoothing was applied by local linear regression over 31-year time spans. The reconstructed March temperature series at Kyoto revealed some cold periods with temperatures of 4–5 °C; ∼3 °C lower than present temperatures. These temperature declines coincided with periods of low activity in the long-term solar cycle, namely, the Wolf, Spoerer, Maunder, and Dalton minima. For the 18th and 19th centuries, the reconstructed temperature showed a climatic response delay of about 15 years in relation to the short-term sunspot cycle, which has a periodicity of about 11 years.

The reconstructed temperature changes deduced in this study coincide to some extent with changes deduced from other proxies. To compare temperature estimates deduced in this study with other climatic reconstructions, verification of the spatial and seasonal validity of these results is needed.

Acknowledgements

We are grateful to Dr K. Kodera of the Meteorological Research Institute, Tsukuba, Japan, for information on previous climatic proxies and for comments on the relationship between solar variation and climate change. Partial support was received from the Fukutake Science and Culture Foundation Project for History, in 2004.

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