Reconstruction of April temperatures in Kyoto, Japan, since the fifteenth century using the floral phenology of herbaceous peony and rabbit-ear iris

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Reconstruction of April temperatures in Kyoto, Japan, since the 15th century using the floral phenology of herbaceous peony and rabbit-ear iris

Yasuyuki AONO* and Ayaka NISHITANI

Graduate School of Life and Environmental Sciences, Osaka Prefecture University

*Address for correspondence: Gakuen-cho 1-1, Naka-ku, Sakai, Osaka 599-8531, Japan
E-mail: aono@envi.osakafu-u.ac.jp
Phone: +81-72-254-9431

Abstract

We reconstructed April mean temperatures in Kyoto since the 15th century by investigating historical documents such as diaries and chronicles and compiling phenological data series of the full bloom date for herbaceous peony. In order to fill gaps in phenological data series, we used the full bloom date of rabbit-ear iris, an herbaceous plant that flowers at about the same time of the year as herbaceous peony. We obtained floral phenological data covering a total of 278 years. Calibration using modern temperature data showed herbaceous peony phenology to be the preferred data source for April temperature estimation. Variations in the reconstructed April temperatures in Kyoto were synchronous with changes in the solar cycle. In particular, April temperatures were about 2°C lower than at present around the ends of the Spoerer and Maunder grand solar minima, from 1550 to 1590 and from 1690 to 1730, respectively. In addition, the reconstructed April temperatures suggested a time lag in the climate response to solar activity changes that was about 10 years longer than the previously estimated lags in the responses of wintertime and March temperatures. However, further research is needed to accurately quantify this time lag.

Keywords: Herbaceous peony; Phenology; Rabbit-ear iris; Solar variation; Time-lag in climate response

Introduction

To understand the mechanisms of the climate change occurring at present, the periodicity and characteristics of long-term climate change occurring before modern increases in greenhouse gas concentrations must be known. Geological methods (e.g., those using sediments, corals, or stalactites) are suitable for elucidating climate change on timescales longer than millennia (Bradley 2015), whereas methods using historical documents such as old diaries and chronicles have a finer temporal resolution than geological methods and may be more suitable for reconstructing climate change on a scale of decades to centuries.

In Europe, early historical climates have often been reconstructed by using crop harvest records in historical documents. For example, in France, Hungary, and the Czech Republic, warm-season temperatures have been reconstructed from the harvest dates of wine grapes and grain crops (Chuine et al. 2004; Garnier et al. 2011; Kiss et al. 2011; Možný et al. 2012). These agricultural records are proxies of plant phenological events because they reflect the crop growth and development rate. Long-term changes in the day on which plant phenological events such as flowering and leaf budding occur are often analyzed as indicators of climate change (Sparks and Carey 1995; Ahas 1999; Defila and Clot 2001).

The occurrence of plant phenological events (phenophases) tends to depend significantly on the temperature conditions during the period prior to the phenophase of interest, especially in temperate regions. In reconstructing climate using such phenophase, the temperature to be deduced is usually an average of one to several months. Past records of plant phenophases have been successfully used to reconstruct climate change in the Far East. For example, in China, Liu and Fang (2017) compiled plant phenological information and the lake-ice melting dates from poems written by emperors of the Qing Dynasty and used them to reconstruct springtime temperatures in Beijing. Additionally, temperature sensitivities of spring phenophases over long-term periods have often been studied (Wang et al. 2014; Ge et al. 2014).

In Japan, where the custom of observing the flowering of certain plant species has long been popular, many historical documents record the flowering dates of those species, and these phenological records have been successfully used to reconstruct past climate. For example, Aono and Kazui (2008), Aono and Saito (2010), and Aono (2012) used records of the full bloom dates of cherry trees to reconstruct March mean temperatures in Kyoto since the 9th century AD, and Aono and Tani (2014) used records of the advent of autumn tints of maple leaves to reconstruct October mean temperatures in Kyoto since the 13th century AD. In Kyoto, records of phenophases of plant species associated with other seasons are also available, but they have not yet been applied to the reconstruction of temperature.

Various studies have shown that the climate of the Far East, including Japan, is sensitive to the solar cycle (e.g., Shindell et al. 2001; Waple et al. 2002), and, furthermore, that there is a time lag in the climate response to solar activity. However, because most of the temperature reconstructions used in these analyses represent annual averages rather than seasonal or monthly averages, these studies were unable to detect seasonal variations in the lagged climate response to solar activity, although it has often been noted that the effect of the solar cycle on climate may vary depending on the season (e.g., Kodera and Kuroda 2002; Kodera 2006). Knowledge of the seasonal variations in the time lag of the climatic response to solar activity may provide insights into seasonal differences in the mechanisms of the solar influence on climate. In this regard, temperature reconstructions based on plant phenophases may be suitable for detecting seasonal differences in the climate response to solar activity and their variability.

In this study, we reconstructed April temperatures in Kyoto by compiling a phenological dataset of the full bloom dates of herbaceous peony recorded in historical documents. The blossom of this plant once had been viewed in Japan although they have become a little less common in the last 300 years. We therefore deduced a relation between the full bloom date of herbaceous peony and that of rabbit-ear iris, another common herbaceous plant in Kyoto, and applied to the gap-filling method of the phenological series of herbaceous peony. Thus, a less missing phenological data series for herbaceous peony full bloom dates was compiled based on data from both species.

We then compared the variations in reconstructed April mean temperature with changes in March mean temperature and the solar cycle, both of which have been previously reconstructed. Finally, we investigated whether the reconstructed April mean temperatures for the period before modern meteorological observations showed a time lag in the climatic response to solar variation. We also applied this analysis to March mean temperatures in Kyoto, which we had previously reconstructed, and compared the lengths of the detected time lags between March and April.

Phenological data

Plant species

We mainly used the flowering records of herbaceous peony (*Paeonia lactiflora* Pall.) as a source of information for climate reconstruction. Herbaceous peony, a member of the family Paeoniaceae, grows wild in northern China and Siberia. It may have been originally introduced into Japan because its roots were thought to have medicinal value, and its ornamental use began around the 15th to 16th centuries AD. Around the middle of the 18th century, however, cultivation of herbaceous peony was largely abandoned when the woody peony (*Paeonia suffruticosa* Andrews), which requires less time and effort to cultivate, became popular as an ornamental plant. Therefore, we were required to conduct gap-filling using the phenology of other herbaceous plant species with similar flowering season, which was frequently observed and recorded during historical time in Japan. Thus, we focused on the full bloom date of the rabbit-ear iris (*Iris laevigata* Fisch.). Rabbit-ear iris, a herbaceous plant of the family Iridaceae, is distributed naturally in East Asia. At present, it blooms in early to mid-May, usually by producing three buds that bloom in sequence over an extended period. It also tends to be less sensitive to air temperature, as it generally grows in ponds and swamps. This is attributable to the fact that the growth rate of rabbit-ear iris is affected not only by the temperature conditions but also by the water quality, especially ion composition of water in the habitat (Ichihashi et al., 2009). However, considering the completeness of the data in the historical period, rabbit-ear iris was the only herbaceous plant that was available for gap-filling on full bloom date for herbaceous peony in Kyoto. We acquired phenological data on the full bloom dates of herbaceous peony and rabbit-ear iris by examining the many historical documents, such as old diaries and chronicles, that have been maintained in Kyoto since the 15th century AD. The obtained full bloom date of rabbit-ear iris would eventually be applied to gap-filling the missing full bloom date of herbaceous peony.

Acquisition of phenological data deduced form historical documents

In Kyoto, which was the capital of Japan from the 8th to 19th century AD (Figure 1), flowers of various plant species were both viewed and offered to the Imperial palace. We surveyed historical documents in the collections of several institutions, including the Historiographical Institute of the University of Tokyo and the Kyoto Prefectural Library and Archives, and we compiled flowering phenology dates of herbaceous peony and rabbit-ear iris in Kyoto recorded in the documents as well as in newspapers. We regarded the flower-viewing dates of each species recorded in these documents and newspapers as their full bloom dates. Phenological datasets for full bloom dates were compiled independently for each plant species. Since few descriptions of these species are found in historical documents written before the 14th century AD in Kyoto, our historical document investigation covered the period from 1401 to 1880.

We compiled the dates of the following activities related to the herbaceous flowers (listed in order of decreasing reliability of the data): observations of fully bloomed rabbit-ear iris and herbaceous peony, sightseeing excursions and parties held for the purpose of viewing these flowers, reports of gifts of the flowers of these herbs, and mentions of these herbs and their flowers in contemporary Japanese poetry. Where multiple records were available for a given year, we used the most reliable records to infer the full bloom phenophase. However, the records for full bloom date of rabbit-ear iris, which has a long flowering season and less sensitive to temperature, were adopted only in reliable case where the detailed location where the flowers were in full bloom could be determined. The dates were first compiled according to the Japanese calendar and then converted to day of year (DOY) according the modern Gregorian calendar. A brief overview of the lunisolar Japanese calendar, which was used until December 1872, can be found in Aono (2015).

We related the full bloom dates for both species based on the information from our investigation of historical documents. Using the data from the years in which full bloom dates were available for both species, we calibrated an equation to determine the full bloom date of the herbaceous peony from that of rabbit-ear iris. Eventually, the application of this calibration equation led to gap-filling of the missing full bloom date of the herbaceous peony.

We refer to the period before 1881, in which modern meteorological observation began, as the historical period, while the full bloom dates obtained after this period are divided into two categories: data for calibration and for validation. In order to calibrate the relationship between temperature and the full bloom dates of herbaceous peony, we use the reliable full bloom data from the Kyoto Botanical Garden in the 21st century for calibration. The Kyoto Botanical Garden has a total area of 24 ha and are located at the northern edge of the dense urban area of Kyoto. Other data after 1881, including gap-filled full bloom date in missing year, was applied to validate the accuracy of temperature reconstructions.

Historical blossoming phenology data of the two herbs

We obtained the full bloom dates of the two plant species from 43 old documents (Figure 2), which together contained herbaceous peony flowering records covering 185 years and rabbit-ear iris flowering records covering 129 years (Table 1). In particular, a palace diary called *Oyudono-ue-no-nikki* from the 16th century provided many dates for the full bloom status for herbaceous peony, because the dates on which flowers from various places in Kyoto were offered as gifts to the Imperial Palace were recorded.

In the latter half of the 17th century, the full bloom date of the herbaceous peony was around DOY 140, and then it tended to become later through the first half of the 18th century. After the second half of the 18th century, the number of years when the rabbit-ear iris was in full bloom was greater than that of the herbaceous peony. Records from the Myoho-in and Kyo'o Gokokuji temples also provided full bloom dates for rabbit-ear iris for many years during the 18th and 19th centuries. After 1868, when Kyoto ceased to be the capital of Japan, data on the full bloom dates of both species were scarce because there were few old diaries available for reference. As for the recent years, many full bloom days of rabbit-ear iris have been obtained at Ota Shrine, that has been designated a national Natural Monument.

Equation to fill in the gaps in herbaceous peony phenology

The relationship of the full bloom date of herbaceous peony to that of rabbit-ear iris is shown as a scatter plot in Figure 3. To establish this relationship, we used data from 29 years in which the full bloom dates of the two herbs overlapped, from the historical period to the present day. The full bloom dates for both species showed following significant relation:

$$F_{\mathrm{P}}=0.918F_{\mathrm{I}}+16.18 \qquad (r^2=0.59) \qquad (1)$$

where F_{I} is the full bloom date for rabbit-ear iris (DOY), and F_{P} is the full bloom date for herbaceous peony (DOY). This equation accounts for 59 % of the variance in the full bloom date of herbaceous peony. Aono and Saito (2010) also performed gap-filling of cherry blossom phenology based on the date of full bloom of Wisteria in Kyoto, using the relationship with the coefficient of determination of 0.53. Since the significance of the equation among full bloom dates in this study was higher than that of our previous study mentioned above, we decided to apply equation (1) to gap-filling of missing data for herbaceous peony phenology.

Full bloom date of herbaceous peony with missing data filled in

Figure 4 shows the year-to-year variation of the full bloom date of herbaceous peonies, filling gaps data in missing years. Gaps after the 18th century in the full bloom date of the original herbaceous peony, depicted by the white circles, are filled with the estimates from rabbit-ear iris phenology, depicted by the black dots. The gap-filling applying the rabbit-ear iris phenology has allowed data to be available for 278 years for all study period, Then, from 1501 to 1880 of historical period in this study, phenological data for more than half the years became available. In our previous studies on temperature reconstructions deduced from cherry blossom phenology (e.g., Aono and Kazui, 2008), we considered the period during which phenological data were available for more than half of the years as a reliable indicator of changes in reconstructions. In this study, we will apply this phenological series for gap-filled herbaceous peony to reconstruction of temperature, and focus on the results of the reconstructions from the 16th to 19th centuries.

Calibration of the phenological data using observed April mean temperatures

The modern temperature data observed during the calibration period must be corrected for any possible effect of urban warming. Aono and Kazui (2008) reconstructed temperatures from cherry blossom phenology using temperature and full bloom dates for the period from 1911 to 1940, before noticeable urban warming had occurred, as the calibration period. However, in this study, all of the full bloom dates available for calibration against modern meteorological observations were from after 2000, when urban warming had become more pronounced. At present, the meteorological observatory located in central Kyoto is strongly affected by urban warming, whereas the site where the plant phenological data was observed (Kyoto Botanical Garden), which is located out of the central urban area of Kyoto, do not seem to be greatly affected by urban warming. We assumed that the temperatures that we were attempting to reconstruct for the period before the 1880s, when modern meteorological observations began in Kyoto, were not affected by urban warming. To estimate the effect of urban warming in Kyoto, we used the method of Omoto and Hamotani (1979), in which the “urban-free” temperature is calculated by subtracting temperature increases inferred to be due to the urban effect from observed temperatures. The specific calculation method of urban-free temperature and urban warming effect is described in detail by Omoto and Aono (1990/91). As the reference weather station for estimating the magnitude of the urban warming effect in Kyoto, we chose Kameoka weather station, operated by the Kyoto Prefectural Agriculture, Forestry and Fisheries Technology Center, which is 15 km from the Kyoto city center; this reference station was previously used by Aono (2012, 2015). We then used the corrected urban-free temperatures for calibrating the full bloom dates of each species. Eventually, recent-actual temperatures that are affected by urban warming are 1.9°C higher than the corrected, urban-free temperatures.

We performed a linear regression analysis between the monthly mean urban-free temperature in Kyoto and the full bloom date for herbaceous peony. We found the following significant relationships ($p < 0.05$) between the April mean urban-free temperature and the full bloom date (Figure 5):

$$T_{\mathrm{A}} = -0.170\, F_{\mathrm{P}} + 35.50 \quad (r^2 = 0.72) \tag{2}$$

where T_A is the urban-free April mean temperature in Kyoto (°C). This calibration was performed using only the actual full bloom dates of herbaceous peonies since 2001. In order to reconstruct the April temperature, the full bloom date, including the gap-filling data, will be applied to equation (2).

Validation of the temperature reconstructions against observations

We compared reconstructed interannual April mean temperatures for the period after the start of modern meteorological observations with urban-free temperatures in April (Figure 6). Limiting the examples to those used for calibration (2001, 2003, 2006–2020), the temperature estimation error was generally small; the root mean square error (RMSE) of the estimated temperatures was 0.6°C. The dataset for validation was also arranged using reliable herbaceous peony full bloom dates (3 years: 1890, 1891, 1942) and gap-filled full bloom dates (1887, 1895, 1907–1909, 1912, 1914, 1928, 1929. 1939, and the intermittent period since 1976, for a total of 21 years). This dataset for validation yielded an error of 0.9°C in the RMSE. The RMSE of the estimated temperatures for the entire validation data, deduced from the full bloom dates of herbaceous peony only, was 0.7°C, whereas that of temperatures deduced from the full bloom date filled by the rabbit-ear iris phenology was 0.8°C. Because the period during which rabbit-ear iris is in full bloom each year is long, the full bloom dates reported in newspapers and documents may not always correspond to the first day on which most flowers at a site were in bloom, which may have caused their correlation with temperature to be relatively low.

The RMSE of the estimated temperatures in the combined calibration and validation datasets was 0.8°C, which is equal to the RMSE obtained by Aono and Kazui (2008) for March mean temperatures in Kyoto reconstructed using cherry blossom phenological data, as well as to that obtained by Aono (2015) for March mean temperatures in Edo (Tokyo) reconstructed using cherry blossom phenological data. To more accurately show the long-term changes in temperature, Aono and Kazui (2008) smoothed the temperatures reconstructed using cherry blossom phenology data by applying a local linear regression procedure over 31-year time spans, and the accuracy of the reconstruction after smoothing was extremely high (RMSE = 0.1°C; Aono and Kazui 2008). Applying this smoothing method to the reconstructed April mean temperature yielded an RMSE of 0.4°C for the period for which some validation data were available (1896-1937). Additionally, the RMSE of the reconstructed temperature after 1979, including the period used for calibration, was 0.2°C. The underestimation bias in the reconstructed temperature due to urban warming, which was not completely rectified during the calibration period, increased the RMSE compared to our previous results for cherry trees. In this study, we also used local regression to express long-term changes in the reconstructed temperatures.

Reconstructed temperatures during the historical period (1401–1880)

Figure 7 shows reconstructed April mean temperatures from 15th century to the present, before and after smoothing by applying local linear regression over spans of 31 years. The reconstructed temperatures ranged from 10 to 13°C and showed recurring cycles of warm and cold periods. Data on the full bloom phenology of both species were sparse and showed large variability during the 15th century. Thus, the confidence interval for the smoothed data during this period is wide (±0.6～±1.5 °C) and the precision of the estimated temperature is low. During the 16th century, the reconstructed April mean temperature shows a rising trend, and it reached 11°C or higher between 1510 and 1550 before dropping slightly.

During four periods, 1490–1510, 1550–1590, 1630–1660, and 1690–1730, the reconstructed temperatures were about 1.5–2.0°C lower than urban-free temperatures during 1990–2020. In particular, the period from 1690 to 1730, which was an additional 0.5°C cooler compared with the other three cool periods, was the coldest period during the historical period, we have focused in this study. This cold period seems to correspond to the Maunder Minimum, one of the grand solar minima (Figure 8). A cold period corresponding to the Maunder Minimum was also recognized in the March mean temperature series in Kyoto reconstructed by using cherry blossom phenological data (Aono 2015); however, the lowest reconstructed temperature was obtained for 1693, whereas the lowest April mean temperature as reconstructed in this study occurred in 1716. This difference in the timing of the cold periods in temperature reconstructions for different months is further discussed in the next section.

In the 18th century, the reconstructed April mean temperatures for the period after the 1730s were relatively high (11–12℃). Many of the descriptions of floral phenology from this period were recorded in diaries, and because of the large number of data, these temperatures could be reconstructed with high accuracy. From 1531 to 1880 in historical period of this study, the confidence intervals of smoothed reconstructions kept to fall within the range of ±1.0℃ (average; ±0.55℃). However, there are fewer data on full bloom dates for the 19th century and the first half of the 20th century. Thus, the confidence intervals of the smoothed temperatures are wider and the reconstruction accuracy is considerably less. In addition, most of the available floral phenological data from the latter half of the 19th century through the first half of the 20th century are for rabbit-ear iris, and the reconstructed temperatures tended to be underestimated compared to observed values after correction for the urban warming effect. Because many full bloom dates for rabbit-ear iris reported in newspapers were likely later than the earliest full bloom date of this species, owing to the long duration of its flowering period, the reconstructed temperatures were lower than the observed temperatures. In the data from the 1970s and after, the reported full bloom dates are generally the correct dates, so the reconstructed results are reliable and can be used for calibration.

Time lags of the reconstructed temperature series relative to solar activity

We compared the time series of April mean temperatures from 1400 to 1900 reconstructed in this study with the reconstructed (Solanki et al. 2004) and observed (Van der Linden and the SIDC team) time series of the relative number of sunspots, as well as with the time series of March mean temperatures reconstructed by using cherry blossom phenology (Aono and Kazui 2008; Aono 2012) (Figure 8). This 500-year period includes three grand solar minima in the number of sunspots, known as the Spoerer (1420–1570), Maunder (1645–1715), and the Dalton (1790–1820) Minima.

In the reconstructed March mean temperature series (Aono and Kazui 2008; Aono 2012), temperature decreases are observed during the latter half or immediately following each grand solar minimum. In particular, the cooling in the latter half of the 17th century occurred after the decline in solar activity of the Maunder Minimum (Aono 2012). In this study, however, the 17th century decline in the reconstructed April mean temperatures occurred even later relative to the Maunder Minimum. The lowest reconstructed March mean temperature around this time occurred in 1693 (Aono 2015), whereas the lowest reconstructed April mean temperature occurred in 1716.

We therefore conducted cross-correlation analyses to determine the time lags of the climatic response to solar activity. In these analyses, we focused on the 250-year period from 1531 to 1780 during which both the March and April phenological datasets were sufficiently large for continuous temperature reconstruction and determined which 250-year period of reconstructed solar activity (Solanki et al. 2004) was most strongly correlated with each reconstructed temperature time series. For example, if the reconstructed sunspot time series from 1521 to 1770 correlated most strongly with the reconstructed temperature time series from 1531 to 1780, then the time lag of the climate response would be interpreted to be 10 years. Independent cross-correlation analyses were performed for the reconstructed March and April temperature time series.

The results of the cross correlation analysis (Figure 9) showed that the reconstructed March and April temperatures lagged the sunspot number by 12 and 24 years, respectively. The correlations used to determine these time lags were statistically significant at $p < 0.001$.

A clear positive correlation between temperature in Asia and solar activity has been reported (e.g., Shindell et al. 2001; Waple et al. 2002), and the temperature series in the Asian region follows the solar variation with a time lag. For example, Waple et al. (2002) showed that the positive correlation in the Asian region was stronger when a lag of 14 years in the annual mean temperature series relative to the solar cycle was considered. The length of the detected lag in the temperature response varies among different data types. Wang and Zhang (2011), who used annual rings of *Abies* spp. from the Tibetan Plateau to reconstruct temperature, detected a delay in the temperature response time of 13 years. Gray et al. (2013) analyzed sea surface temperatures in the ocean around Japan in winter between 1870 and 2010 and found an 11-year lag relative to solar activity, which is close to the March mean temperature lag of 12 years detected in this study (Figure 9), deduced from the analysis of reconstructions in Kyoto (Aono and Kazui, 2008; Aono, 2012). However, the April temperature lag (24 years) detected in Kyoto in this study is 13 years longer than the wintertime lag detected by Gray et al. (2013).

These results suggest that in Japan the time lag of the long-term variation of temperature with respect to the solar cycle may be longer during the transition between winter and summer when the seasonal temperature is increasing. However, the April temperature reconstructions deduced in this study had only a relatively low correlation with the solar cycle. It is difficult to clearly detect the precise time lag of the reconstructed April temperature in this study from the solar variation. This is because all lags we set give similar relatively low correlation coefficients, as shown in Figure 9. Reconstruction of temperature series, deduced from more robust phenological information, also might prevents the influence of artifacts during statistical processing as used in this study.

Our previous study on the March temperature reconstructions showed high accuracy because we chose the date of full bloom of cherry trees, which have high sensitivity to temperature, for the analysis. In this study, we attempted to reconstruct the April mean temperature using phenology for herbaceous plants, which are more sensitive to the local environment. In order to accurately reconstruct the general environmental conditions in Kyoto, we should combine phenological data for woody plants, which are likely to be highly sensitive to April temperatures. However, the amount of phenological information for such plants in historical documents is less than that of cherry flower, so it is necessary to combine the phenology of various plants into an index. Several previous studies integrated time series of the phenophases of multiple plants into a single index that reflects climate conditions for the purposes of climate analysis and reconstruction (Kiss et al. 2011; Ault et al. 2015; Liu and Fang 2017). If time series of phenophases of multiple plants became be available for specific season, we might apply a method to indexation of climate conditions, proposed by previous studies mentioned above.

In order to correctly quantify the time lag in the climatic response during the warming season, it will be also necessary to perform further temperature reconstructions for other months. However, in Kyoto, the accurate reconstruction of temperatures for other than spring have not been deduced from plant phenological records. For example, Aono and Tani (2014), who used the autumn tint phenology of maple leaves to reconstruct temperatures in Kyoto in autumn (October), when temperatures are falling, detected almost no delay with respect to the solar cycle; however, their result is inconclusive because very few phenological data were available from the first part of the 17th century.

In Japan, we have not yet identified a phenophase that can be used to reconstruct historical midsummer temperatures. It might be possible to reconstruct the midsummer climate in Kyoto during the historical period by deriving the summertime rainy day ratio from daily weather records in historical documents, but this analysis is both time consuming and difficult, especially if there is even a slight gap in the daily weather records. Tagami (2016) used daily weather records in historical documents from the 11th to the 16th century to estimate the rainy day ratio in summer in Kyoto, but their reconstruction of the midsummer climate has many gaps. The use of plant phenology to reconstruct temperature has the advantage that literature surveys can provide monthly temperature reconstructions that are relatively easy to process and can be used for detailed analyses. Thus, one of our next challenges is to identify and investigate phenological events that will allow us to reconstruct temperatures in different months and seasons.

Conclusions

We investigated the full bloom dates of two herbaceous species, herbaceous peony and rabbit-ear iris, in Kyoto since the 15th century and used them to reconstruct mean temperatures in April. The full bloom phenological data were collected from historical documents such as diaries, and chronicles, and, more recently, from newspaper articles and social networking sites. A series of full bloom dates for herbaceous peony was compiled. Rabbit-ear iris floral data were applied to filling gaps in herbaceous peony phonological series. Using both species, we obtained data for a total of 278 years.

We calibrated the relationship between the phenological data and April mean temperature using modern (2001, 2003, 2006 to 2020) phenological data for herbaceous peony. The full bloom date of the herbaceous peony was significantly correlated with temperature (r^2=0.72). The reconstructed April temperatures declined in 1550–1590 and 1690–1730, periods corresponding to grand solar minima of sunspots. In these periods, the temperature was about 2°C lower than present-day temperatures that have been corrected for the effect of urban warming. Thus, the reconstructed April temperatures appeared to be influenced by the solar cycle but the April temperature response lagged the solar cycle by about 20 years; this time lag is about 10 years larger than the reported lags in winter and in March temperatures. The results of this study cannot explain the reason for this difference in the temperature response, and its clarification will require analyses of the responses in both midsummer and autumn. Among temperature reconstruction methods, ones using plant phenophases, which reflect plant growth and development under the influence of the environment in a particular month, are worthy of more attention in the future.

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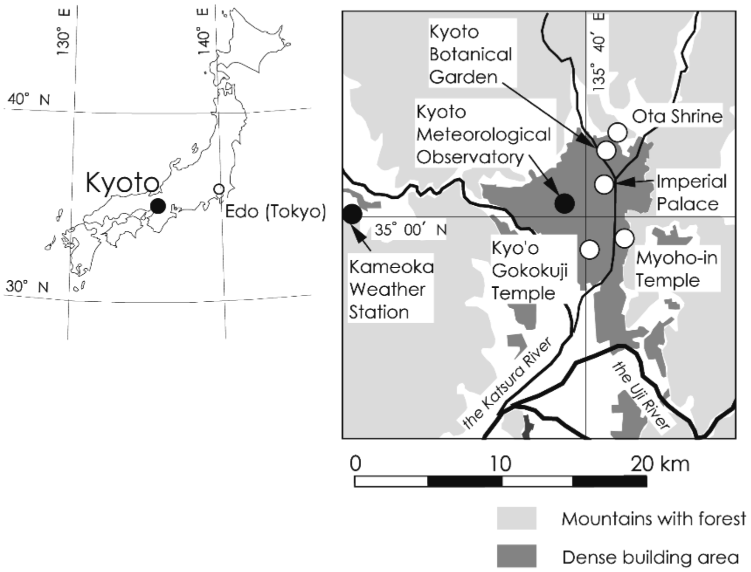

Figure 1. Map of the Kyoto area. Modern temperature observations were made at sites shown by solid circles, and the locations where many historical phenological events were observed are shown by open circles.

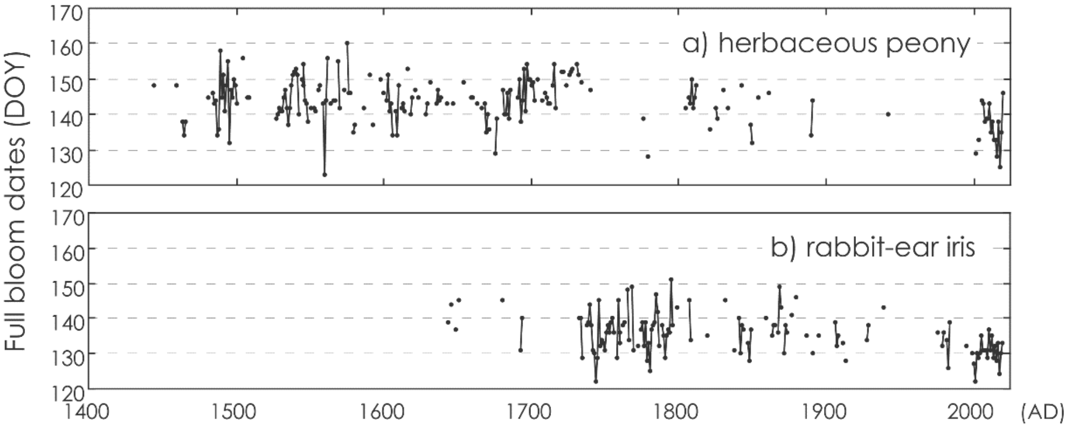

Figure 2. Interannual variation in the full bloom dates of (a) herbaceous peony (*Paeonia lactiflora*) and (b) rabbit-ear iris (*Iris laevigata*), acquired from historical diaries and chronicles.

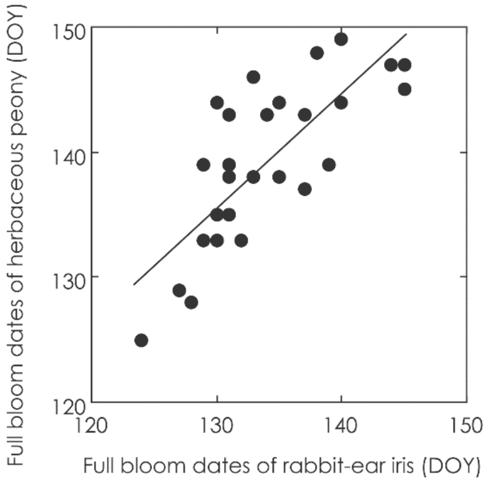

Figure 3. Correlation between the full bloom dates of herbaceous peony and rabbit-ear iris. The relationship was made for years in which data on the full bloom dates of both were available, from the 17th to the 21st century. Regression equation (1) was also shown.

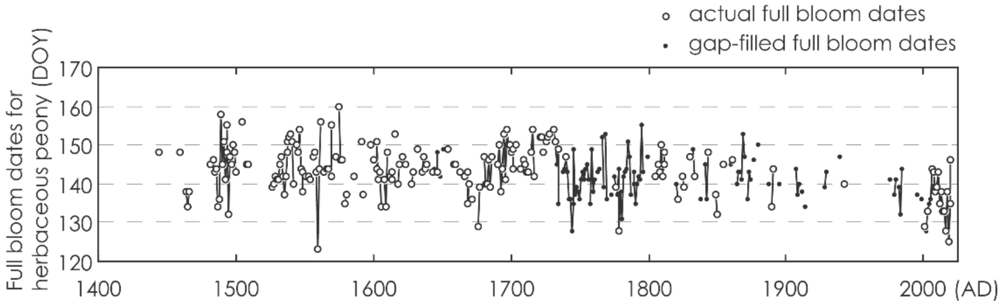

Figure 4. Interannual variation in the date of full bloom of herbaceous peony after gap-filling with rabbit-ear iris phenology.

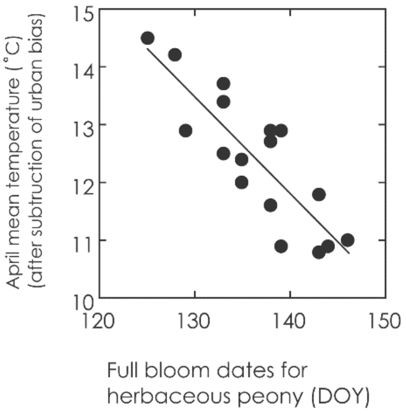

Figure 5. Relationships between the full bloom dates of herbaceous peony (2001–2020 with three years of missing data) and April mean temperature (after subtraction of urban warming bias). Regression equation (2) was also shown.

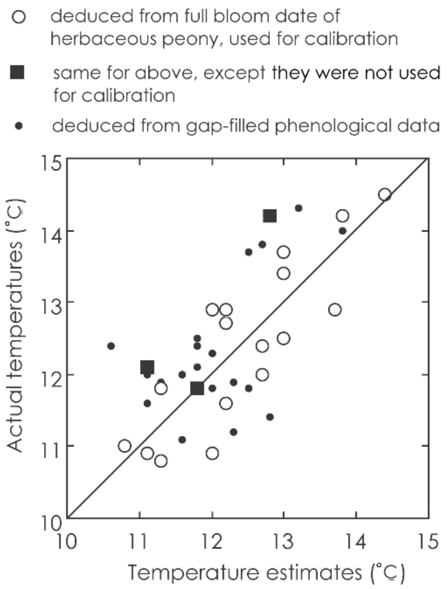

Figure 6. Observed and estimated April mean temperatures for each year from 1881 to 2020. Observed temperatures have been corrected to urban-free values.

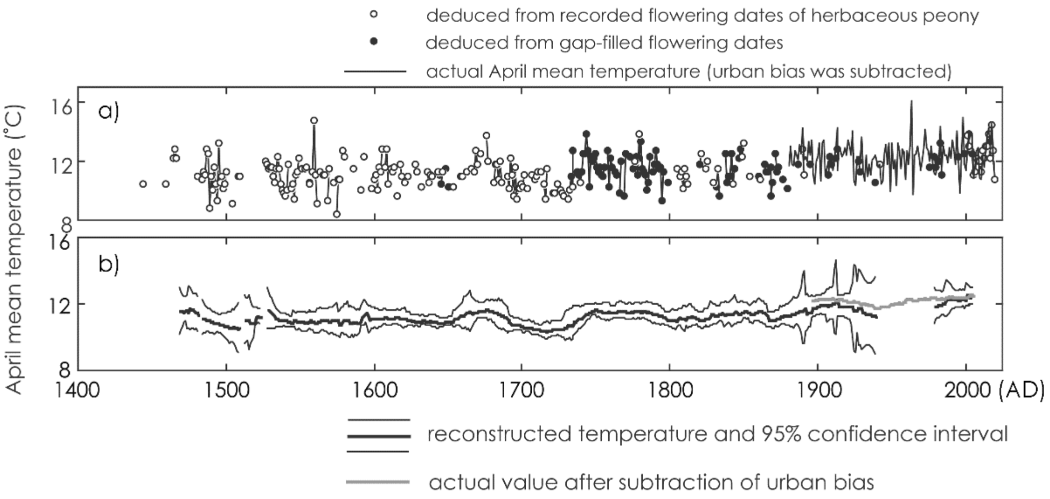

Figure 7. (a) Temperatures reconstructed by using the full bloom dates of herbaceous peony in Kyoto from the 15th century to 2020, and (b) the temperature time series after smoothing by applying local linear regression over spans of 31 years.

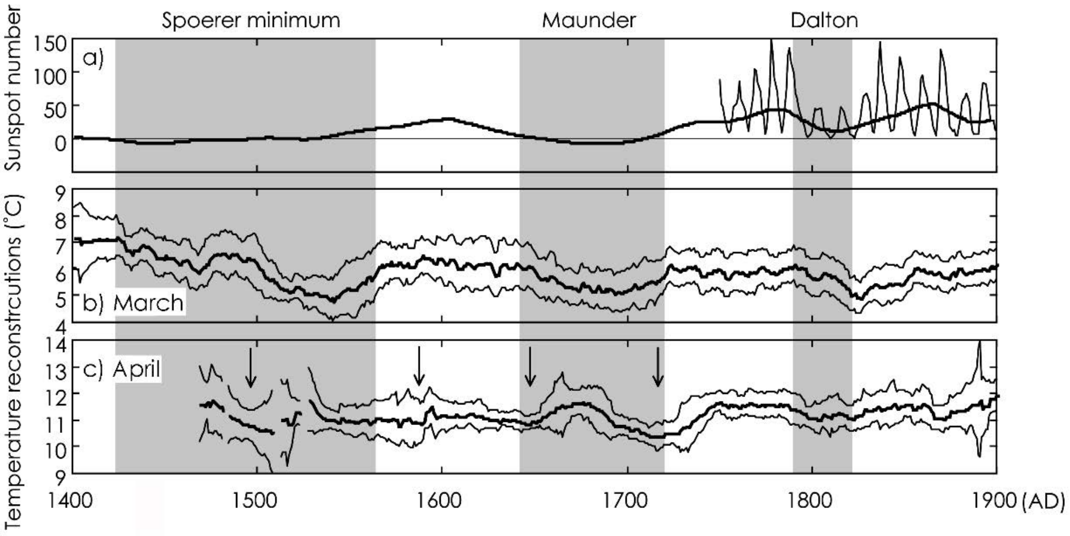

Figure 8. (a) Reconstructed sunspot numbers (Solanki et al. 2004; heavy line), with decadal-scale fluctuations smoothed, and observed relative sun spot numbers (Van der Linden and the SIDC team, thin line). (b) Reconstructed March mean temperatures (Aono and Kazui 2008; Aono 2012). (c). April mean temperatures reconstructed in this study. Periods of grand solar minima are shaded gray. The downward arrows show the cold periods mentioned in the text.

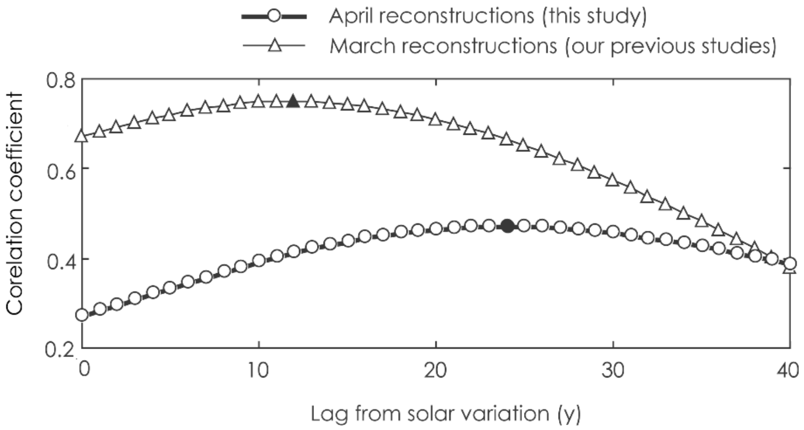

Figure 9. Results of cross-correlation analyses between time series of reconstructed solar variation (Solanki et al. 2004) from 1531 to 1780 and reconstructed temperatures for March and April. For each month, the solid symbol shows the time lag of the temperature change, as indicated by the maximum correlation obtained between each temperature time series and the solar variation time series.

Table 1. Number of data by recording source for each century of phenological information.

Century	Number of data by data source				Number of data before gap-filling	Number of data after gap-filling
	Diary	Other documents	News paper	SNS		
	(Herbaceous peony)					
15	23	0	0	0	23	23
16	49	1	0	0	50	50
17	52	0	0	0	52	56
18	23	0	0	0	23	74
19	16	1	2	0	19	38
20	1	0	0	0	1	17
21	0	0	0	17	17	20
Total	164	2	2	17	185	278
	(Rabbit-ear iris, applied to gap-filling)					
15	0	0	0	0	0	
16	0	0	0	0	0	
17	7	0	0	0	7	
18	54	1	0	0	55	
19	27	1	3	0	31	
20	1	0	15	0	16	
21	0	0	0	20	20	
Total	89	2	18	20	129	