INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **26**: 2117–2127 (2006)
Published online 23 May 2006 in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/joc.1356

EARLIER SPRING IN SEOUL, KOREA

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Received 11 May 2005
Revised 17 March 2006
Accepted 26 March 2006

ABSTRACT

In the present study, long-term changes in the first bloom date of shrub and tree species in Seoul (126.56 °E, 37.34 °N), Korea were examined using historical observational data for the period 1922–2004 (83 years). The study focused on two shrub species, golden-bell (*Forsythia koreana*) and azalea (*Rhododendron mucronulatum*), and three tree species, cherry (*Prunus yedoensis*), peach (*Prunus persica*), and American locust (*Robinia pseudoacacia*). The annual-mean temperature has increased by about 2 °C in Seoul over the 83 years analyzed. The temperature increase is significant during the winter and early spring and becomes less significant during late spring. As a result of this regional warming, all five species showed an advance in the first bloom date over this time period. The advanced date is particularly apparent in early-spring flowering species like golden-bell (-2.4 days 10-year^{-1}), azalea (-2.4 days 10-year^{-1}), cherry (-1.4 days 10-year^{-1}), and peach (-1.4 days 10-year^{-1}) as compared to late-spring flowering species like American locust (-0.5 days 10-year^{-1}).

The present results have demonstrated that the major factor for the determination of flower blooming is heat accumulation, i.e. a certain threshold of growing degree-days (GDD) index. In particular, early spring flowers were sensitive to the accumulation of warm temperature than late-spring flowers. Copyright © 2006 Royal Meteorological Society.

KEY WORDS: global warming; urbanization; flowering; growing degree-days; Seoul

1. INTRODUCTION

Atmospheric concentrations of greenhouse gases such as CO_2, CH_4, and N_2O have drastically increased above the preindustrial level over the twentieth century. The increase in the concentrations of these gases are largely due to human activities and, because of their efficient infrared absorption of terrestrial radiation, result in anthropogenically enhanced greenhouse warming, which is commonly known as global warming. It was reported that the global-mean surface air temperature has increased by 0.6 ± 0.2 °C during the last 100 years (Intergovernmental Panel on Climate Change (IPCC), 1995, 2001). This warming trend is more evident over mid- and high-latitudes in the winter hemisphere.

Across the globe, the impact of global warming on the climate system leads to climate changes such as enhanced precipitation and evaporation and more intense and frequent rainstorms (IPCC, 1995, 2001; many references therein), which in turn lead to rising sea levels. At the regional/local scale, climate changes in meteorological variables present a rather complex set of phenomena. In conjunction with global and local climate changes, many characteristics of ecological systems, such as the temporal and/or spatial distributions of forests and crop yields, should undergo alteration. Particularly, change of the accumulated warmer temperature, i.e. growing degree-days (GDD) (hereafter), may trigger changes in phenological events, although phenological

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processes themselves involve many sophisticated factors. The most noteworthy plant impacts of global warming are most likely to occur in phenological events such as the time of flowering, unfolding of leaves and leaf senescence.

Global warming is known to modulate patterns of seasonality in the annual temperature distribution (Hunter and Lechowicz, 1992). Accordingly, a great deal of attention has been focused on the investigation of historical phenological records. In Europe and North America, the early onset of phenological spring has been well documented by many plant ecologists and meteorologists (e.g. Myneni *et al*., 1997; Walkovszky, 1997; Schwartz, 1998; Alward and Detling, 1999; Schwartz, 1999; Menzel, 2000; Schwartz and Beiter, 2000; Abu-Asab *et al*., 2001). Walkovszky (1997) found that the locust tree showed a shift toward an early-flowering date in Hungary and an extension of its growing season by 10.8 days since the early 1960s. Menzel (2000) documented that leaf-unfolding in spring has advanced by 6 days in Europe during the 1959–1993 period. It should be noted that the relationship between climate change and an early phenological date in spring may represent different characteristics for different flower species. Moreover, Abu-Asab *et al*. (2001) found that different plant species showed different changing rates for flowering dates in the Washington DC area for the 1970–1999 period: the rate of change in earlier-flowering species ranges from −3.2 to −46.0 days and that of later-flowering species ranges from 3.1 to 10.4 days.

Beside various responses of phenological events in species, the features of global warming signals are quite different in different parts of the globe (IPCC, 2001). Therefore, corresponding changes in phenology would be expected to differ in diverse regions, e.g. from continent to continent. Schwartz and Beiter (2000) revealed that the move toward an early onset of phenological spring exhibits strong regional dependency in North America, primarily in the northwestern United States and southwestern Canada. Apart from studies focusing on Europe and North America, there are some studies that examine the global warming-flower bloom relation over East Asia (Chen and Pan, 2002; Schwartz *et al*., 2006). The purpose of this study is to investigate historical shrub and tree flowering data (1922–2004) in Seoul, Korea, one of the fast growing metropolitan cities in the world, and to provide an assessment of changing flowering dates in some tree species corresponding to regional warming.

Concerning changes in phenological events in association with temperature variations, the urban heat island effect should be included. For example, it is shown that similar plants growing inside an urban zone and in nearby rural areas show significantly different changes in phenology (Min, 2000). However, it may not be easy to separate those two influences (i.e. global warming *vs* urban heating effect) from phenological data sets. If we conduct long-term observations outside and inside the city, we could possibly separate the effects of global warming from urbanization. This work will be presented in a separate paper.

The present study is arranged in the following manner. Data used in this study are shown in Section 2. Long-term changes in surface air temperature and flowering date are analyzed in Section 3. The relation between flowering date and GDD is displayed in Section 4. Discussion and a summary are presented in Section 5.

2. DATA

The daily-mean surface air temperature at Seoul meteorological station (126.56 °E, 37.34 °N, 86 m elevation) utilized in the present study is derived from the Korean Meteorological Administration data archives. Surface air temperature data are available from October 1907 up to the present, with a missing period from 1950 to 1953 corresponding to the Korean War. The area of the nation is about 300 km × 500 km, and its weather is mainly controlled by the same midlatitude synoptic system. So temperature observations in Seoul well represent nationwide variations even on the daily timescale.

The phenological garden is located inside Seoul meteorological station. This meteorological/phenological station is surrounded by short vegetation and grass in the center of the city. The first bloom dates of two shrub species, golden-bell (*Forsythia koreana*) and azalea (*Rhododendron mucronulatum*), and three tree species, cherry (*Prunus yedoensis*), peach (*Prunus persica*), and American locust (*Robinia pseudoacacia*) are also examined in this study. The timing of first blooming has been observed once every year for the five flowering

DOI: 10.1002/joc

species and is available from 1922 to the present, with the 1950–1953 period missing. The time of observation of the first fully opened flowers is recorded as the first bloom date of the tree. To minimize the effects of tree aging, the trees in the phenological garden have been replaced at regular intervals of between 15 and 25 years, depending on the species.

Interestingly, the date of first blooming was unexpectedly early (or late) in some years, i.e. about 1 month earlier (or later) than the long-term average. However, there was no reason to remove an extremely early or late bloom from the original data sets, and we did not do so because the variance might have corresponded to the actual warm and cold years. So, we tried to include all possible data sets for analysis in the present study. In this study, the analysis period was confined to the years 1922–2004 when both temperature and flowering data sets were available.

The present study expressed long-term changes in the spring-flowering date. Thus, using an objective statistical method was critical to decide whether change signals were significant for the analyzed periods. The t-test was applied in this study.

3. CHANGES IN TEMPERATURE AND FLOWERING TIME

Consistent with the trends of global warming and fast urbanization mentioned previously, the annual-mean temperature in Seoul shows a gradual increase for the entire period (Figure 1(a)). On the whole, the time series indicate two regime shifts, in the late 1950s and late 1980s-early 2000s. It is also noted that these two regime shifts were detected from the changing point analysis, i.e. 1958 and 1989 with 99% confidence level. The detailed methodology of the changing point analysis is found in Chan and Shi (1996). The magnitude of temperature increase is about 1.0 °C for each regime shift period. Therefore, the annual-mean temperature was higher by 1.0 °C in the early 2000s, when compared to the period 1960–1989, and 2.0 °C when compared to the period 1922–1949. This change rate of 2.0 °C over the entire data period is about three times the global-mean value of 0.6 °C.

As shown in Figure 1(a), the warming trend is much clearer in the late 1980s and early 1990s. For example, the number of years having an annual-mean temperature above 13 °C is zero until the 1970s, one in the 1980s, and three in the 1990s. While the interannual variability of temperature is large, the significance of the warming trend exceeds the 95% confidence level, which is large enough to assert that there is a 'significant' increase in the annual-mean temperature.

For a detailed examination of long-term temperature changes, variations in monthly-mean temperatures are shown in Figure 1(b). Similar to the two regime shifts in the annual-mean temperature, there are two periods showing a jump each month. Also, it is interesting to note that the time series of monthly-mean temperatures show a steeper increase in the earlier months than in the later months: temperature differences between the approximately 20-year periods, 1922–1940 and 1981–2000 are 2.0 °C in February, 2.3 °C in March, 1.9 °C in April, and 1.3 °C in May. These different monthly change rates can be observed in other midlatitude regions (IPCC, 2001). The warming trend in Seoul has been reported in a lot of literature (e.g. Kim *et al*., 1999; Ha *et al*., 2004) and it is known to be very significant, as well.

Where the initiation of blooming in most plants is cued by photoperiodism, actual blooming is triggered by an accumulation of warm temperature (Salisbury and Ross, 1992). Because the annual photoperiodic cycle has presumably not changed for the analysis period, long-term variations of phenological dates are almost certainly related to local warming. So, changes in plant phenology would be a good indicator of climate change over the globe and even in the local area. However, the measurement of flowering dates is undertaken only once each year for each species. To obtain a reliable relationship between temperature and flowering time, therefore, the analysis of a long historical data set is required.

Figure 2 shows the time plots of the phenological dates of flowering in months and days for the five spring-flowering woody species for the period 1922–2004. While all five species show an advanced first bloom date (negative slope in the figure), the rate of change varied greatly among the species, from −2.4 days 10-year^{-1} to −0.5 days 10-year^{-1}. Here, the trend was calculated on the basis of a linear regression method. Overall, the occurrence of early flowering is more apparent in early-spring flowering species like golden-bell (−2.4 days

DOI: 10.1002/joc

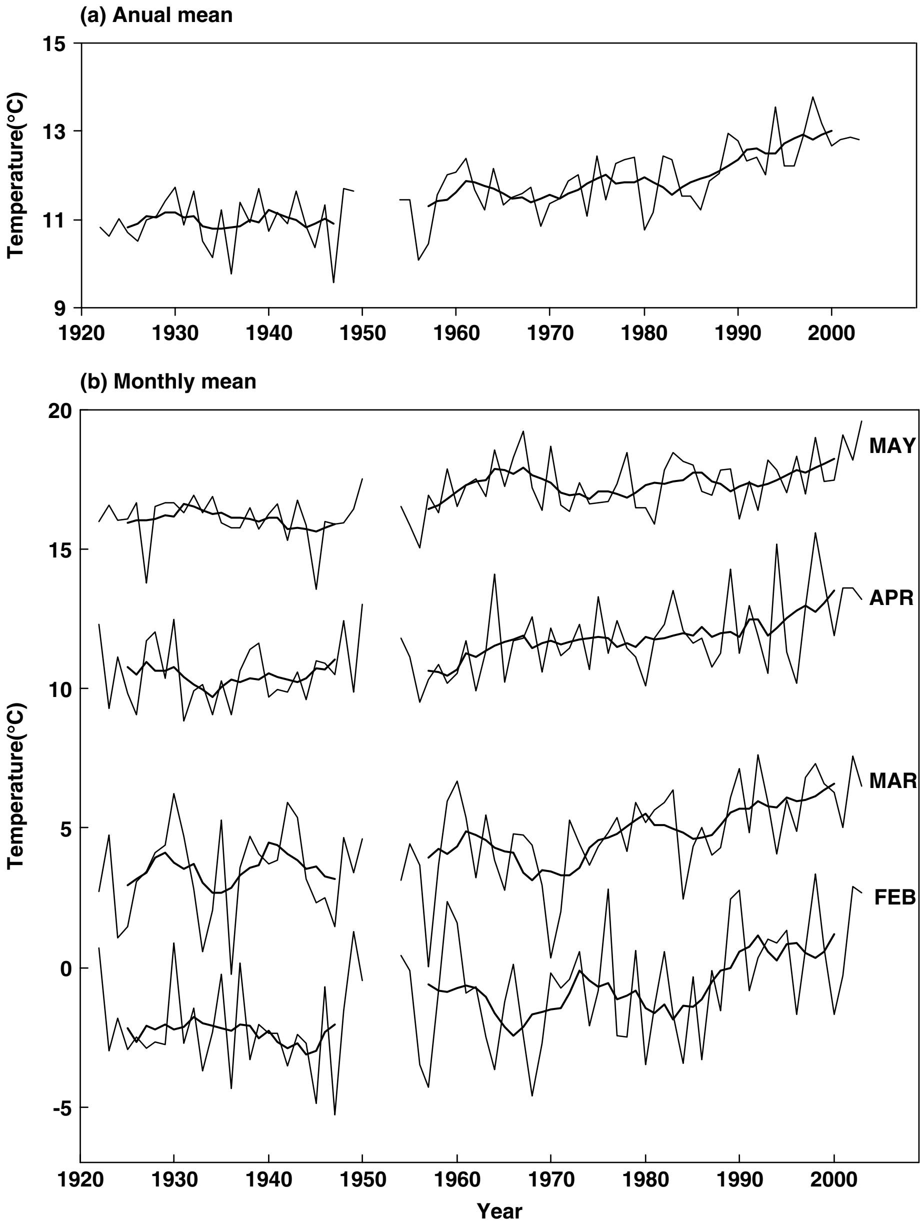

Figure 1. Time series of annual-mean temperature (a) and monthly mean temperature (b) in Seoul, Korea for the period 1922–2004. The thick solid line denotes the 5-year running average

10-year^{-1}), azalea (-2.4 days 10-year^{-1}), cherry (-1.4 days 10-year^{-1}), and peach (-1.4 days 10-year^{-1}) compared to late-spring flowering species like American locust (-0.5 days 10-year^{-1}). The t-test proves that the change rates of all four early-spring flowering species are significant at the 95% confidence level.

The changes in the first flower bloom date of the five tree species are probably not due to an artifact of plant aging, because old trees would be expected to delay the start of flower blooming (Menzel and Fabian, 1999). Thus, the advance of flowering time clearly represents plants responding to the temperature changes. Consistent with our results, it was reported that plants have an intrinsic genetic mechanism to sense ambient temperature such that flowering time is advanced by an increased temperature and delayed by

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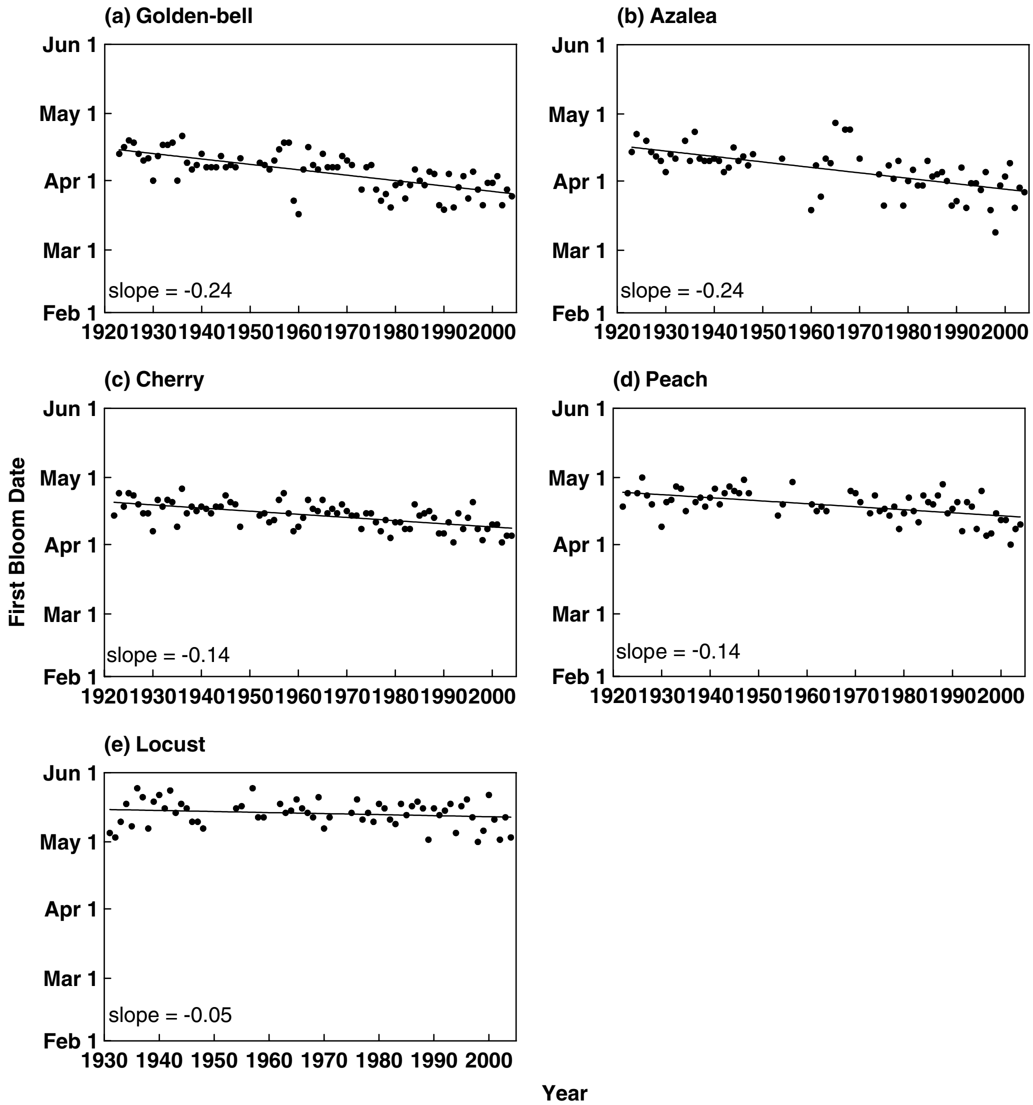

Figure 2. Variations of first bloom date of five tree species: golden-bell (a), azalea (b), cherry (c), peach (d), and American locust (e). The sold line shows the linear slope

chilling (Blázquez *et al.*, 2003; Kim *et al.*, 2004). Also, the response is apparent in early-spring flowering trees, which is consistent with a steep temperature increase in February and March (see Figure 1(b)). This earlier flowering observed in all five species may be attributed to changes in the reproductive phases in these plants.

4. GROWING DEGREE-DAYS (GDD) *VERSUS* FLOWERING TIME

The timing of phenological events such as first leaf emergence, flowering, and fruiting respond to accumulating heat units to some degree (Larcher, 2003). In addition, day length and other environmental factors can also give rise to variations in phenological activities. The GDD index is one of the indices that is used to express the growth of plants, closely related to the time of flowering (Cannell, 1989) and the development of fruits

DOI: 10.1002/joc

(Rathcke and Lacey, 1985). The GDD index is calculated by subtracting a base temperature (e.g. usually defined as 5 °C) from daily-mean temperature, an average of the maximum and minimum temperatures, in a single day. Indeed, this calculation expresses the fact that no noticeable growth is observed at temperatures cooler than the base temperature. The values of GDD at the time of flower bloom may not have obviously changed because each spring tree species requires a certain threshold value of the daily cumulative temperature for a successful flowering event.

The applications of the GDD model are quite common in phenological literature and involves three apparent issues; (1) Not all plants have a 5 °C base temperature. Obtaining the base temperature would require running each species with numerous base temperatures to come up with the best fit. (2) Because flowering time (days) and GDD are correlated, the analysis should be done with deviations from the long-term mean GDD, and (3) the best fit may be sensitive to the starting date of GDD summing (Snyder *et al*., 1999). In addition to the above three issues, the usage of minimum temperature and/or maximum temperature instead of daily-mean temperature may influence the determination of GDD. However, it is found that the change rate of minimum (maximum) temperature is almost similar to that of the daily mean (figure not shown). So, different use of temperatures (i.e. minimum, maximum, and daily mean) may not influence the results.

In the present study, we calculated the base temperature for the five species considering all the above three concerns. Regarding the second issue, the long-term mean GDD was subtracted everyday to find the smallest standard deviation of GDD (i.e. best fit calculation). Table I presents the GDD-derived base temperature, mean GDD, and standard deviation of GDD for two different starting dates, such as 1 January(a) and 1 February(b). On the whole, the GDD-derived base temperature is not sensitive to variation of the starting date of GDD summing; Table I(a) and (b) are quite similar. The t-test also shows no meaningful difference in the base temperature by choosing the starting dates, either 1 January or 1 February. This is true for mean GDD and its standard deviation, as well. So, we defined the base temperature as follows: golden-bell and azalea at 4 °C, cherry and peach at 5 °C, and locust at 8 °C. The GDD is obtained by measuring accumulating warmer temperature than the specified base temperature from the first date of the year (i.e. starting from 1 January) until the flowering date.

Figure 3 shows the variation of the GDD with time for the five species. Generally, no significant trend of change is detected except for the American locust tree, as seen in the figure. For golden-bell and azalea (Figure 3(a) and (b), respectively), the mean GDD is 84.2 °C and 96.1 °C varying within ±30 °C in most years. The standard deviation is 25.2 °C for golden-bell and 38.3 °C for azalea. While the GDD of cherry, 106.2 °C, is larger than that of golden-bell and azalea because of its relatively late-flowering time, its interannual variations show a very small value, i.e. 16.2 °C standard deviation (Figure 3(c)). Also, relatively small interannual

Table I. The base temperature, mean GDD, and standard deviation of GDD obtained from a starting date, 1 January(a) and 1 February(b). The standard deviation is calculated on the basis of GDD anomaly

	Base temperature (°C)	Growing degree-days (°C)	
		Mean	Standard deviation
(a) 1 January			
Golden-bell	4.1	84.2	25.2
Azalea	4.0	96.1	38.3
Cherry	5.5	106.2	16.2
Peach	5.3	138.0	29.1
Locust	8.3	233.1	46.7
(b) 1 February			
Golden-bell	4.4	82.7	25.5
Azalea	4.3	94.5	39.1
Cherry	5.8	105.3	16.2
Peach	5.8	137.1	29.1
Locust	8.7	232.9	46.8

variations with a large GDD value, 138.0 °C, are shown for peach (Figure 3(d)). The standard deviation of peach GDD is 29.1 °C. The timing of first bloom for American locust occurs in mid May, so a larger GDD value, 233.1 °C, is observed (Figure 3(e)).

As can be seen in Figure 3, relatively early-spring flowers such as golden-bell, azalea, cherry, and peach show small standard deviation values, while relatively later spring flower such as American locust shows large standard deviation values. This discrepancy implies that the most important factor for flowering in the earlier spring flowers is an accumulation of warm heat. These species commence blooming as soon as they obtain enough GDD exceeding a certain threshold value. By contrast, the later spring flower is not as sensitive to the GDD threshold value. It may be influenced by length of day, soil moisture, and other environmental factors, as well.

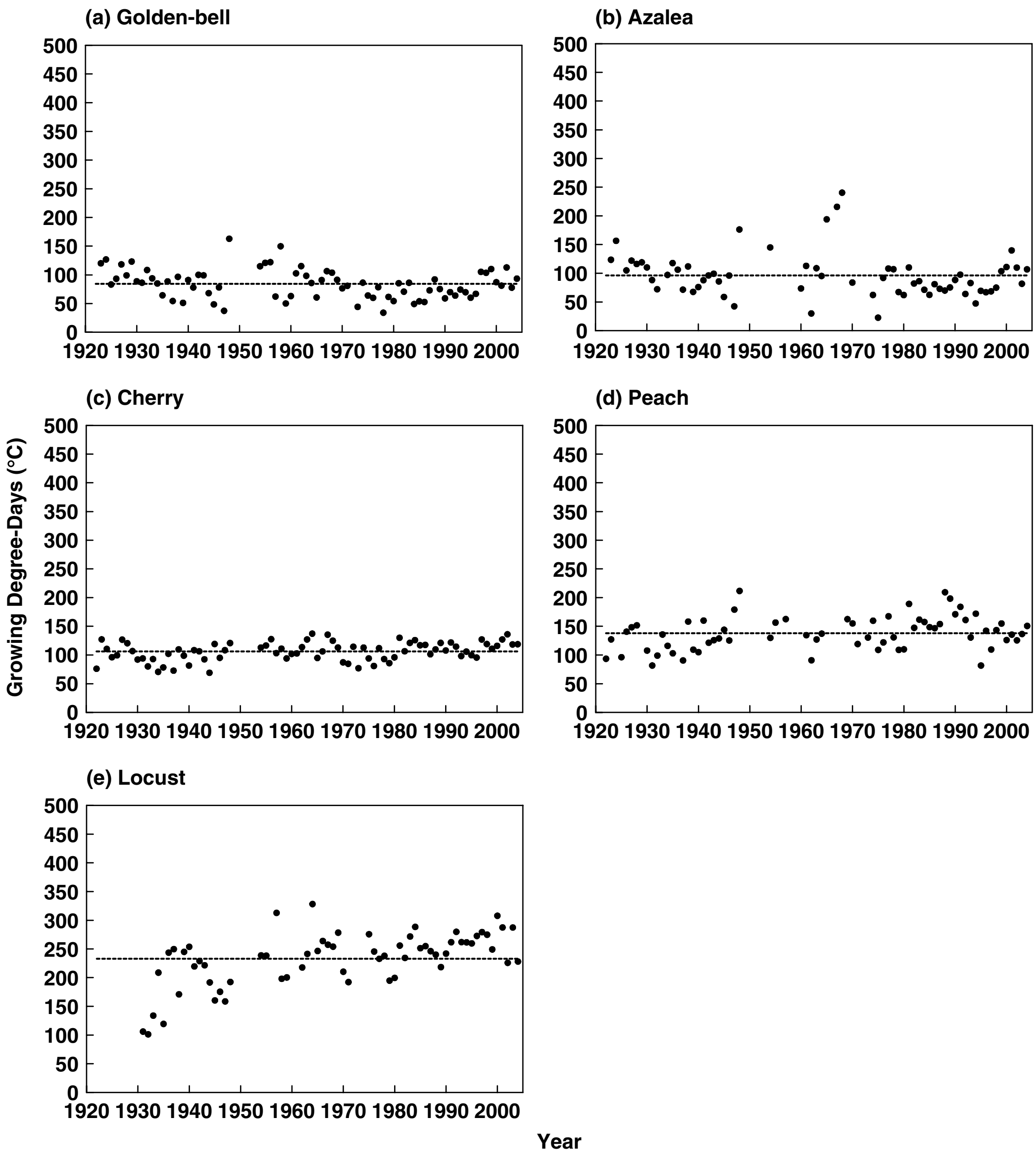

Figure 3. Same as in Figure 2 except for growing degree-days (°C, GDD) at the date of first bloom. The dotted line shows the average value of GDD for the period

DOI: 10.1002/joc

Combining all the above figures (Figures 1–3), the scatter plots of flowering time *versus* critical date for exceeding the mean GDD value for the five species are presented in Figure 4. Consistent with little changes in the GDD value at the date of flower bloom with time (see Figure 3), the slope of the scatter plots is about 1 except in the case of American locust. As seen in Figure 4, the correlation coefficients between slope and scatter plots are as follows: golden-bell 0.82, azalea 0.74, cherry 0.89, peach 0.78, and American locust 0.54. The correlation coefficients for the first four species exceed the 99% confidence level. The relatively low correlation coefficient for American locust is a reflection of weak temperature dependency of its flowering time.

5. DISCUSSION AND SUMMARY

Surface air temperature is one of the most important factors during the phenological phase of temperate deciduous forests. It indicates that the plant that has an annual rhythm that is more responsive to spring weather than that of any other season. Thus, indices that measure the timing of flower bloom and the unfolding of leaves can be biological symptoms of global warming (or climate change) and/or urban heating. This study demonstrated that surface air temperature has increased in Seoul, Korea over the last 83 years (1922–2004). The enhanced annual-mean temperature is about 2 °C for the period, and this increase is marked during the winter and early spring and is relatively weak in late spring.

The present results clearly displayed that the two shrubs and three tree species illustrate an earlier bloom date over time. The rate of change varies among species from −2.4 days 10-year^{-1} to −0.5 days 10-year^{-1}. The advanced date of flower bloom is more evident in early-spring flowering species like golden-bell (−2.4 days 10-year^{-1}), azalea (−2.4 days 10-year^{-1}), cherry (−1.4 days 10-year^{-1}), and peach (−1.4 days 10-year^{-1}) when compared to late-spring flowering species like American locust (−0.5 days 10-year^{-1}). Overall, these findings are similar to earlier spring rates in Europe (−2.1 days 10-year^{-1}; Menzel, 2000) and North America (−1.7 days 10-year^{-1}; Schwartz and Beiter, 2000).

The variations of GDD index were also examined to investigate the effect of thermal energy on changing flowering time. It was found that the GDD values in the date of flower bloom are almost constant for the early-spring flowers. Relatively large variations were observed in the late-spring flower. These discrepancies clearly designated that earlier spring flowers are sensitive to the accumulation of warm temperature compared to later spring flowers. Also, the scatter plots of flowering time *versus* critical date exceeding the mean GDD value show a slope of 1 except for American locust. This slope of 1 would be another supporting verification for the temperature dependency of flowering.

On the basis of the above results, the focal factor for the determination of flower blooming is heat accumulation, i.e. a certain threshold of GDD, for the five spring species that are widely observed in Seoul and the Korean peninsula. By definition, the GDD value accumulates when the daily-mean temperature is warmer than the base temperature (usually 4–5 °C in midlatitude). As can be seen from monthly-mean temperatures in Figure 1(b), there is no year when the mean is greater than 5 °C for the month of February. In March, there are only few years when the mean is greater than 5 °C until the 1980s. After that, most years exceed 5 °C. Therefore, it is to be expected that the numbers of relatively warm daily temperatures (>5 °C) for the two months (February and March) are the most important factors influencing variation of the timing of flower bloom.

Figure 5 shows the correlation coefficients between flowering time and 10-day mean temperature from early February to the mean flowering date for the analyzed species. In American locust, the correlation coefficients are obtained starting from early March. While American locust shows characteristics that are quite different, the other four species show similar behavior. For the four woody species, the absolute magnitudes of correlation coefficient are low in early February and show an abrupt increase in mid- and late-February. This high negative correlation coefficient is maintained for about 1 month, i.e. the whole of March. The variations in the correlation coefficient indicate that those for daily temperatures in late February and all of March are equally important for the determination of flowering time. For American locust, on the other hand, the correlation coefficients start to increase from mid March to late April. However, the absolute magnitude is much smaller than the other four species.

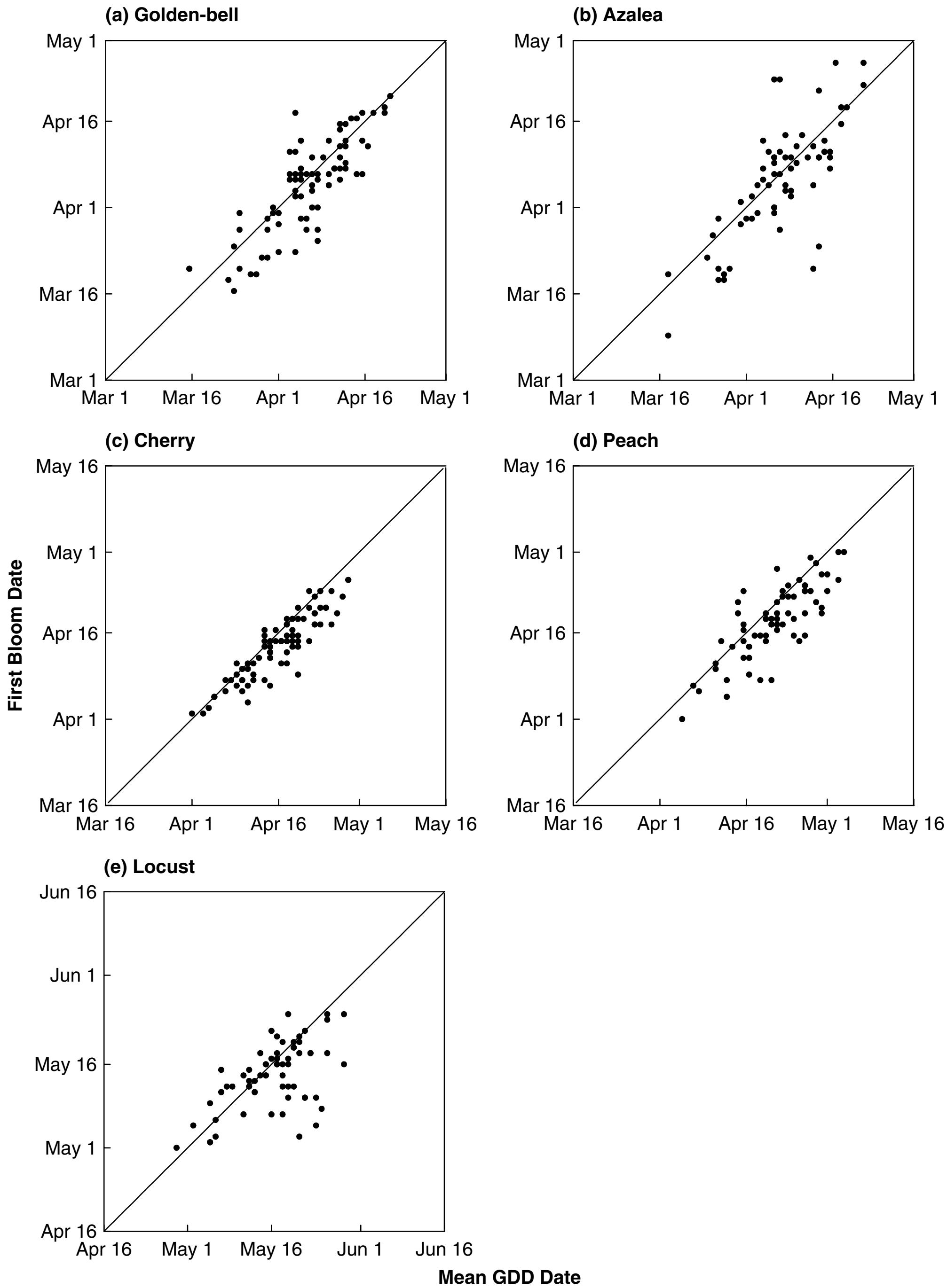

Figure 4. Scatter plots of first bloom date *versus* GDD date. The GDD date is defined when GDD exceeds the average value shown in Fig. 3

In conclusion, the present results included the following three key issues: (1) distinguishing early- and late-flowering species, (2) incorporating species differences in determining base temperature and GDD, and (3) attempting to identify critical time periods that boost the earlier arrival of spring. As discussed in many previous studies, since phenological events are controlled mainly by temperature changes, the adjusted

DOI: 10.1002/joc

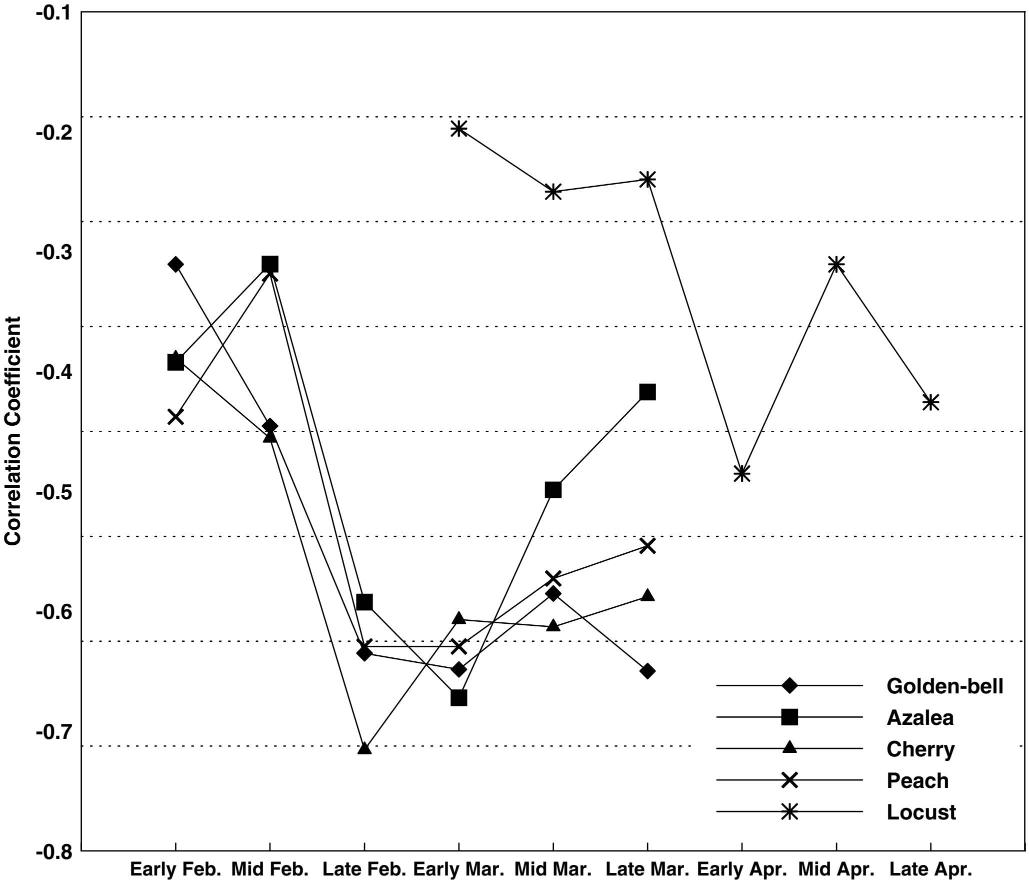

Figure 5. Correlation coefficients between flowering time and 10-day mean temperature for five tree species

phenological phase even on the local scale may reflect global warming and/or climate change successfully. Therefore, the signal of earlier flowering date may be important information for not only adaptation of the plant to changing climate but also detection of climate change in the global ecosystem by using flowering dates.

ACKNOWLEDGEMENTS

This study was supported by grant No. 3345-20060004 from the Basic Research Program of the Korea Science & Engineering Foundation. The flowering data were provided by the Korean Meteorological Administration, which archives, manages, and distributes this data. The authors thank Mr Hyung-Seok Kim for making figures. The clarity of the paper has been significantly improved owing to the suggestions made by an anonymous reviewer

REFERENCES

Abu-Asab MS, Peterson PM, Shetler SG, Orli SS. 2001. Earlier plant flowering in spring as a response to global warming in the Washington, DC, area. *Biodiversity and Conservation* **10**: 597–612.

Alward RD, Detling JK. 1999. Grassland vegetation changes and nocturnal global warming. *Science* **283**: 229–231.

Blázquez MA, Ahn JH, Weigel D. 2003. A thermosensory pathway controlling flowering time in Arabidopsis. *Nature Genetics* **33**: 168–171.

Cannell MGR. 1989. Chilling, thermal time and the date of flowering of trees. In *Manipulation of Fruiting*, Wright CJ (ed). Butterworth and Co: London.

DOI: 10.1002/joc

Chan JCL, Shi JE. 1996. Long-term trends and interannual variability in tropical cyclone activity over the western North Pacific. *Geophysical Research Letters* **23**: 2765–2767.
Chen X, Pan W. 2002. Relationships among phenological growing season, time-integrated normalized difference vegetation index and climate forcing in the temperature region of eastern China. *International Journal of Climatology* **22**: 1781–1792.
Ha KJ, Ha EH, Yoo CS, Jeon EH. 2004. Temperature trends and extreme climate since 1909 at big four cities of Korea. *Korean Journal of the Atmospheric Sciences* **40**: 1–16.
Hunter AF, Lechowicz MJ. 1992. Predicting the timing of budburst in temperate trees. *Journal of Applied Ecology* **29**: 597–604.
Intergovernmental Panel on Climate Change (IPCC). 1995. *Climate Change 1995: The Science of Climate Change, Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, Houghton JT, Meiro Filho LG, Callander BA, Harris N. (eds). Cambridge University Press: New York.
Intergovernmental Panel on Climate Change (IPCC). 2001. *Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, Houghton JT, Ding Y, Griggs DJ, Noguer M. (eds). Cambridge University Press: New York.
Kim HJ, Hyun YB, Park JY, Park MJ, Park MK, Kim MD, Kim HJ, Lee MH, Moon JH, Lee IH, Kim JM. 2004. A genetic link between cold responses and flowering time through FVE in *Arabidopsis thaliana*. *Nature Genetics* **36**: 167–171.
Kim MK, Kang IS, Kwak CH. 1999. The estimation of urban warming amounts due to urbanization in Korea for the recent 40 years. *Korean Journal of the Atmospheric Sciences* **35**: 118–126.
Larcher W. 2003. *Physiological Plant Ecology*, 4th edn. Springer-Verlag Telos: Germany.
Menzel A, Fabian P. 1999. Growing season extended in Europe. *Nature* **397**: 659.
Menzel A. 2000. Trends in phenological phases in Europe between 1951 and 1996. *International Journal of Biometeorology* **44**: 76–81.
Min BM. 2000. Comparison of phenological characteristics for several woody plants in urban climates. *Journal of Plant Biology* **43**: 10–17.
Myneni RB, Keeling CD, Tucker CJ, Asrar G, Nemani RR. 1997. Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature* **386**: 698–702.
Rathcke B, Lacey EP. 1985. Phenological patterns of terrestrial plants. *Annual Review of Ecological System* **16**: 179–214.
Salisbury FB, Ross CW. 1992. *Plant Physiology*, 4th edn. Wadsworth Publishing Company: Belmont, CA.
Schwartz MD. 1998. Green-wave phenology. *Nature* **394**: 839–840.
Schwartz MD. 1999. Advancing to full bloom: Planning phenological research for the 21st century. *International Journal of Biometeorology* **42**: 113–118.
Schwartz MD, Beiter BE. 2000. Changes in North American spring. *International Journal of Climatology* **20**: 929–932.
Schwartz MD, Ahas R, Aasa A. 2006. Onset of spring starting earlier across the northern hemisphere. *Global Change Biology* **12**: 343–351.
Snyder RL, Spano D, Cesaraccio C, Duce P. 1999. Determining degree-day thresholds from field observations. *International Journal of Biometeorology* **42**: 177–182.
Walkovszky A. 1997. Changes in phenology of the locust (*Robinia pseudoacacia* L.) in Hungary. *International Journal of Biometeorology* **41**: 155–160.

DOI: 10.1002/joc