Evaluation of Chilling and Heat Requirements in Japanese Apricot with Three Models

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Abstract. Estimating chilling requirements is crucial for identifying appropriate cultivars for a given site, for timing applications of dormancy-breaking chemical agents, and for predicting consequences of climate change. For temperate-zone fruit species such as Japanese apricot, productivity is reduced when chilling requirements are not adequately satisfied. In our study, we obtained chilling and heat requirements for flowering of six Japanese apricot cultivars, which spanned the range of flowering times in this species for three successive years. Different methods for determining chilling requirements were evaluated and compared, and correlations among chilling requirements, heat requirements, and flowering date were established. The dynamic model proved to be the best for determining the chilling requirements of Japanese apricot. The results showed a range of chilling requirements ranging from 26.3 to 75.7 chill portions and a narrow range of heat requirements, from 1017.7 to 1697.3 growing degree-hours (GDH). A very high correlation ($R = 0.9797$) between flowering date and chilling requirements and a low correlation ($R = 0.4298$) between flowering date and heat requirements suggest that flowering date in Japanese apricot is mainly a consequence of the chilling requirements of the different genotypes, whereas heat requirements contribute a limited effect to the variation in flowering dates. Chilling requirements and heat requirements were positively related with a low correlation coefficient ($R = 0.4211$).

Japanese apricot (*Prunus mume* Sieb. et Zucc.) originated in China and has been widely cultivated in Asia for ≈3000 years (Chu, 1999). Owing to its charming flowers and flavorful fruit, it has been widely planted as an ornamental plant and an economic fruit tree; its fruit is consumed as a preserve and a drink in China (Shi et al., 2009). The cultivars of Japanese apricot in Taiwan have the lowest chilling requirements in the world (Ou and Chen, 2003). Owing to being greatly restricted by climatic conditions, especially related to chilling accumulation, the

distribution of Japanese apricot is limited to East Asia, including China, Japan, and Korea; it is rarely cultivated in other countries (Ou and Chen, 2003). Therefore, we studied the chilling and heat requirements of Japanese apricot to help producers breed new cultivars and to assist horticulturists in other countries to introduce the appropriate cultivars.

The study of the phenological behavior of crops, as part of a well-characterized environment, is important both to obtain satisfactory production and to determine the most suitable agronomic techniques (Valentini et al., 2001). Many fruit and nut crops require chilling accumulation in winter to break dormancy. Quantifying this chilling requirement and selecting appropriate cultivars for the climate of a given region are crucial for successful cultivation of such crops. If the chilling requirement is not satisfied, budbreak will be uneven and delayed, shoot vigor will be reduced, and flower development will be poor (Campbell and Sugano, 1975). On the other hand, in the case of low chilling requirements (e.g., early-flowering cultivars growing in cold-winter areas), blooming happens too early and freezes can reduce yield (Bartolini et al., 2006). The information of the chilling requirement of a cultivar has significant practical and economic impacts on the control, maintenance, and production of woody plants (Fennell, 1999) and is necessary for crop management of Japanese apricot cultivars in their most suitable areas.

To better quantify winter chilling accumulation, past researchers have developed several chilling models. Temperature has been described as the most decisive climatic factor. The Weinberger model (Weinberger, 1950), still widely used, is the oldest method to quantify winter chilling accumulation. The Utah model (Richardson et al., 1974), which is most widely used, contains a weight function assigning different chilling efficiencies to different temperature ranges, including negative contributions by high temperatures. The dynamic model (Fishman et al., 1987a, 1987b), which overcomes some difficulties of the Utah model, especially in mild-winter climates, postulates that winter chilling accumulates in a two-step process. Initially, cold temperatures lead to the formation of an intermediate product. Once a certain quantity of this intermediate has accumulated, it can be transformed into a “chill portion.” In this age of global warming, many researchers have tested which chilling model is best in different regions of the world (Luedeling, 2009a, 2009b, 2009c, 2011; Rahemi and Pakkish, 2009).

The difficulty that a number of deciduous fruit trees have in adapting to environmental conditions different from those of their origin is well known and is mainly the result of the need for adequate satisfaction of their chilling requirements for flowering. Problems related to the inaccurate selection of cultivars with unsuitable chilling requirements affect Japanese apricot production. Many growers used winter chilling accumulation to determine the timeline for certain management measures, such as the spraying of rest-breaking chemical agents, or to predict yield potential (Erez, 2000).

Once the chilling requirements have been satisfied, heat is required for full bloom. However, studies on heat requirements are fewer and the effects of heat requirements on flowering date are less known (Citadin et al., 2001; Couvillon and Erez, 1985; Gariglio et al., 2006). Methods of determining the heat requirements for flowering have been developed (Anderson et al., 1986; Richardson et al., 1974). It is still not clear what the relation is between heat requirements and chilling requirements for flowering.

It is imperative that the chilling requirements of Japanese apricot should be determined to prevent the future planting of cultivars that will not perform well under the predicted climate change scenarios. Some researchers used different methods to determine the chilling requirements of Japanese apricot (Ou and Chen, 2003; Wang et al., 2007; Yamane et al., 2006). Up to now, unfortunately, no systematic calculation of chilling requirement has been developed for Japanese apricot cultivars and new selections.

The purpose of our study was the calculation of the chilling and heat requirements for flowering of Japanese apricot cultivars during the full range of flowering time in three successive years. We also evaluated and compared different methods for determining chilling requirements and established correlations

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Table 1. Chilling accumulation under field conditions according to the Utah model, dynamic model, and Weinberger model.^z

Yr	30 Nov.	31 Dec.	31 Jan.	28 Feb.	15 Mar.
Chill units (Utah model)					
2009–10	286	727	1068	1389	1585
2010–11	203	482	693	1002	1150
2011–12	–46	320	786	1224	1448
Mean	147	509	849	1205	1394
SD	174	205	195	194	222
CV (%)	118	40	23	16	16
Hours (Weinberger model)					
2009–10	318	634	1004	1322	1537
2010–11	203	497	811	1150	1350
2011–12	103	417	883	1354	1565
Mean	208	516	899	1275	1484
SD	108	110	98	110	117
CV (%)	52	21	11	9	8
Portions (dynamic model)					
2009–10	16	40	62	80	91
2010–11	10	30	50	69	78
2011–12	7	29	51	72	82
Mean	11	33	54	74	84
SD	5	6	7	6	7
CV (%)	42	19	12	8	8

^zThe date of chilling accumulation was from 1 Nov. to 15 Mar.

among chilling requirements, heat requirements, and flowering date. This information can be used to advise Japanese apricot farmers about the cultivars best suited to their area and which areas are the most appropriate for production.

Materials and Methods

Plant materials. The plant material comprised six Japanese apricot cultivars spanning the full range of flowering time. The early flowering cultivars were ‘Taoxingmei’ and ‘Shuangshuidaroumei’, the late flowering cultivars Fenghou and Yanhua, and the medium flowering cultivars Dongqing and Xiyeqing. All the cultivars were grown in the National Field Genebank for Japanese apricot (altitude 10 m, lat. 32°03′ N, long. 118°46′ E) located in Nanjing, Jiangsu Province, China. The trees were eight years old at the beginning of the study, and all trees received similar cultural practices such as irrigation and fertilization.

Sample collection. The experiments were conducted in three consecutive years (2009–12) in the experimental orchard of the National Field Genebank for Japanese apricot (Nanjing, China). Hourly temperatures were collected from November to April by a thermohygrograph and an automatic data logger (Hangzhou Instrument Co., Ltd., Hangzhou, China).

From the beginning of the chilling accumulation, five branches of each cultivar (with lengths of ≈25 cm and diameter of 5 mm) were collected weekly from trees in the orchard and the bases were placed in a 5% sucrose solution in a growth chamber, making a fresh cut at the base of the branches. The branches were maintained at 25 ± 1 °C under white fluorescent tubes (55 μmol·m⁻²·s⁻¹) during a photoperiod of 16 h and at 18 ± 1 °C

during the dark period of 8 h with a constant relative humidity of 70%. The sucrose solution was refreshed and bases cut every 3 d. The development stage of the flower buds was recorded after 10 d in the growth chamber.

Determination of chilling and heat requirements. The start date for chilling accumulation was considered to be when a consistent chilling accumulation occurred and the temperatures producing a negative effect (chilling negation) (Erez et al., 1979; Guerriero et al., 2002; Richardson et al., 1974) were rare. Both physical and physiological parameters were used to determine the date of breaking of dormancy (Campoy et al., 2010, 2012; Guerriero et al., 2002; Ruiz et al., 2007). From the sampled branches, three replicates of 20 flower buds were sampled before and after forcing. The date of breaking of endodormancy was established when, after 10 d in the growth chamber, 30% of the flower buds were in Baggiolini’s stage B to C (green tip) (Baggiolini, 1952), and there was at least an average 30% increase in bud weight. The chilling requirements coincided with the chilling accumulated until the date of dormancy release. Determination of chilling requirements was by hours between 0 and 7.2 °C for the Weinberger model (Weinberger, 1950), chill units for the Utah model (Richardson et al., 1974), and chill portions for the dynamic model (Fishman et al., 1987a, 1987b).

The equations for the Weinberger model are as follows (Weinberger, 1950):

$$CH_t = \sum_{i=1}^t T_{7.2}, \text{ with}$$

$$T_{7.2} = \begin{cases} 0^\circ\text{C} < T < 7.2^\circ\text{C} & : 1 \\ \text{else} & : 0 \end{cases}$$

The equations for the Utah model are as follows (Richardson et al., 1974):

$$Utah_t = \sum_{i=1}^t T_{ui}, \text{ with}$$

$$T_{ui} = \begin{cases} T \leq 1.4^\circ\text{C} & : 0 \\ 1.4^\circ\text{C} < T \leq 2.4^\circ\text{C} & : 0.5 \\ 2.4^\circ\text{C} < T \leq 9.1^\circ\text{C} & : 1 \\ 9.1^\circ\text{C} < T \leq 12.4^\circ\text{C} & : 0.5 \\ 12.4^\circ\text{C} < T \leq 15.9^\circ\text{C} & : 0 \\ 15.9^\circ\text{C} < T \leq 18.0^\circ\text{C} & : -0.5 \\ T > 18.0^\circ\text{C} & : -1 \end{cases}$$

The equations for the dynamic model are as follows (Darbyshire et al., 2011; Fishman et al., 1987a, 1987b):

$$x_i = \frac{e^{\frac{\text{slp} \cdot \text{tetml} \cdot t_i}{T_k}}}{1 + e^{\frac{\text{slp} \cdot \text{tetml} \cdot t_i}{T_k}}}$$

$$x_s = \frac{a_0}{a_1} \cdot e^{\frac{e_1 - c_0}{T_k}}$$

$$ak_1 = a_1 \cdot e^{\frac{e_1}{T_k}}$$

$$\text{int } er_E = x_s - (x_s - \text{int } er_s) \cdot e^{-ak}$$

$$\text{int } er_s =$$

$$\begin{cases} t = t_0 & : 0 \\ t > t_0 \wedge \text{int } er_{E-1} < 1 & : \text{int } er_{E-1} \\ t > t_0 \wedge \text{int } er_{E-1} \geq 1 & : \text{int } er_{E-1} \cdot (1 - x_i) \end{cases}$$

$$\text{delt} = \begin{cases} t = t_0 & : 0 \\ t > t_0 \wedge \text{int } er_E < 1 & : 0 \\ t > t_0 \wedge \text{int } er_E \geq 1 & : x_i \cdot \text{int } er_E \end{cases}$$

$$CP_t = \begin{cases} t = t_0 & : \text{delt} \\ t \geq t_0 & : \text{delt} + CP_{t-1} \end{cases}$$

Accordingly, the constants a_0 , a_1 , e_0 , e_1 , slp , and tetml were set to 1.395×10^5 , 2.567×10^{18} , $4,153.5$, $12,888.8$, 1.6 , and 277 , respectively. T_k is the measured hourly temperature in Kelvin, whereas t denotes the time during the season (in hours) with t_0 being the starting point of chilling accumulation.

Heat requirements were calculated as GDH following the model proposed by Richardson et al. (1974). GDHs are hourly average temperatures (°C) minus 4.5 °C, which are accumulated daily. For each cultivar, heat requirements were calculated as the number of GDH accumulated between the end of dormancy and the date when 50% of flowers were open (F_{50}) in the orchard. The length of this period was expressed as the increment of Julian days (delta JD). We determined delta JD as a complement for GDH, because delta JD is highly dependent on the temperature conditions of the area and year.

Statistical analysis. Statistical analyses were performed using SPSS 17.0 for Windows (SPSS Inc., Chicago, IL) and Duncan’s multiple range test. Correlation coefficients were determined as Pearson’s coefficients. The differences between groups were determined by Tukey’s b test ($P < 0.01$). The cvs ($\sigma/\mu \times 100$) were calculated to assess the variability of chilling requirement among cultivars and years using the different models.

Results

Chilling accumulation under field conditions. Under field conditions, chilling accumulation during November was rather low; in 2011–12, it had a negative value as measured by the Utah model (Table 1). The most efficient months for chilling accumulation were from December through February, although the first fortnight of March also contributed considerably in some years (Table 1). The lowest chilling accumulation in March was registered in 2010–11 with 1150

chill units compared with 1584.5 in 2009–10 and 1447.5 in 2011–12.

Data among years were more homogeneous with the dynamic and Weinberger models than with the Utah model. Variability was very high with the Utah model. cv for chilling accumulation until 15 Mar. was 15.9% with the Utah model, 8.0% with the dynamic model, and 7.9% in the case of the Weinberger model.

Chilling requirements for breaking of dormancy. Differences in bud weight on cuttings were evident between cultivars, and the

end of dormancy was sharper in some cultivars than in others (Fig. 1). Bud weight of ‘Fenghou’ and ‘Yanhua’ did not increase as much as that of the other four cultivars despite considerable chilling accumulation, probably because they did not accumulate enough chilling requirements that year or because few flower buds were present.

The cultivars showed a wide range of chilling requirements for flowering from 26.3 to 75.7 chill portions (Table 2). ‘Taoxingmei’ and ‘Shuangshuidaroumei’ completed dormancy on accumulation of 32 and 26.3 chill portions, respectively, and were classified as low-chilling cultivars. The chilling requirements of ‘Dongqing’ and ‘Xiyeqing’ were intermediate with 57.7 and 64 chill portions. ‘Fenghou’ and ‘Yanhua’ showed high chilling requirements with values of 72.7 and 75.7 chill portions. The cv of the chilling requirements for blooming for all of the evaluated cultivars considered together was very different depending on the method; the cv was 27.1% with the Utah model, 16.5% with the dynamic model, and 23% with the Weinberger model. The cv among years differed significantly, ‘Shuangshuidaroumei’ having the highest (25.9).

Our results indicate a high positive correlation between chilling requirements and flowering date and between chilling requirements and date of dormancy breaking with a correlation coefficient close to $R = 0.98$, respectively, in the three models of chilling estimation (Table 3). There was a negative correlation between chilling requirements and delta JD.

Heat requirements for flowering. The mean heat requirements for the cultivars ranged from 1017.7 to 1697.3 GDH. Some cultivars, Shuangshuidaroumei and Fenghou, showed similar values in the three years, whereas important differences were observed in other cultivars (Table 4). No significant differences in the heat requirements were found among cultivars with strong differences in F_{50} (Table 4). However, significant differences were found among cultivars as well as among years with regard to the delta JD. The mean values of the delta JD ranged from 15.7 in ‘Yanhua’ to 47.7 in ‘Shuangshuidaroumei’. The low chilling cultivar Shuangshuidaroumei showed the highest delta JD, whereas the high chilling cultivar Yanhua showed the lowest delta JD. In ‘Taoxingmei’ and ‘Shuangshuidaroumei’, the results were practically the same over the three years. In contrast, ‘Xiyeqing’ and ‘Yanhua’ showed very different delta JD values in different years (Table 4).

The relationship between chilling requirements for breaking of dormancy and heat requirements for flowering was positive (Table 3) and the correlation coefficient was not very high ($R = 0.4211$). The highest correlation coefficient was obtained in the case of chill portions (dynamic model). The correlation coefficients were higher when delta JD and chilling requirement values were analyzed, and they ranged from $R = -0.8092$ in hours among 0 to 7.2 °C to

Fig. 1. Increase in weight of the flower buds on excised cuttings with chilling accumulation in six Japanese apricot cultivars in three successive years. Vertical axis represents average weight of 20 flower buds, which indicate the bud development, and horizontal axis represents chilling requirement measured by the Utah model.

Table 2. Chilling requirements for flowering of the Japanese apricot cultivars determined by three models (Weinberger model, Utah model, and dynamic model).

Cultivar	Yr	Date of breaking dormancy	Chill units (Utah model)				Hours (Weinberger model)				Chill portions (dynamic model)			
			Value	Mean	SD	CV (%)	Value	Mean	SD	CV (%)	Value	Mean	SD	CV (%)
Taoxingmei	2009–10	5 Jan.	795				443				41			
	2010–11	29 Dec.	460	567 a ^z	198	35	224	332 a	110	33	29	32 a	8	25
	2011–12	30 Dec.	446				330				26			
Shuangshuidaroumei	2009–10	25 Dec.	684				315				34			
	2010–11	22 Dec.	401	479 a	180	38	149	239 a	84	35	24	26 a	7	26
	2011–12	23 Dec.	352				252				21			
Dongqing	2009–10	10 Feb.	1349				1045				67			
	2010–11	11 Feb.	893	1054 ab	256	24	780	875 b	147	17	57	58 b	9	16
	2011–12	31 Jan.	920				801				49			
Xiyeqing	2009–10	24 Feb.	1275				891				74			
	2010–11	18 Feb.	814	1040 ab	231	22	668	828 b	139	17	62	64 b	9	14
	2011–12	5 Feb.	1031				924				56			
Fenghou	2009–10	8 Mar.	1563				1230				82			
	2010–11	4 Mar.	1070	1323 b	247	19	959	1148 b	162	14	67	73 b	8	11
	2011–12	28 Feb.	1336				1248				69			
Yanhua	2009–10	8 Mar.	1563				1230				82			
	2010–11	25 Feb.	948	1321 b	328	25	855	1141 b	253	22	72	76 b	6	7
	2011–12	21 Feb.	1453				1337				73			

^zWithin columns, means followed by the same letter do not differ significantly at the 5% level, according to Duncan's multiple range test.

Table 3. Correlations between various factors related to the breaking of dormancy and time of flowering in Japanese apricot.

Factor	Variables correlated	Correlation coefficient (R) ^z
delta JD ^y	GDH	−0.4887
delta JD	Chill units	−0.8107
delta JD	Portions	−0.9414
delta JD	Hours between 0–7.2 °C	−0.8092
delta JD	F ₅₀	−0.8928
delta JD	Date of dormancy breaking	−0.9667
GDH	Chill units	0.3348
GDH	Portions	0.4211
GDH	Hours between 0–7.2 °C	0.2995
GDH	F ₅₀	0.4298
GDH	Date of dormancy breaking	0.4331
Chill units	F ₅₀	0.9788
Chill units	Date of dormancy breaking	0.9821
Portions	F ₅₀	0.9797
Portions	Date of dormancy breaking	0.9909
Hours between 0–7.2 °C	F ₅₀	0.9806
Hours between 0–7.2 °C	Date of dormancy breaking	0.9783
F ₅₀	Date of dormancy breaking	0.9741

^zR = correlation coefficient.

^yThe length of the period from the breaking of dormancy to the F₅₀ (50% of opened flowers) date in the experimental orchard.

JD = Julian days.

R = −0.9414 in chill portions. There was a limited correlation between heat requirements and the flowering date.

Flowering date. Flowering dates differed among cultivars (Table 4). The earliest-flowering cultivar was 'Shuangshuidaroumei', which flowered between 5 Feb. and 10 Feb., although differences were observed between years. 'Shuangshuidaroumei' flowered 42 days earlier than 'Fenghou'. 'Dongqing' and 'Xiyeqing' were classified as middle-flowering, because their flowering date was around mid-March. The latest-flowering cultivars were 'Fenghou' and 'Yanhua' with flowering date on 28 Mar. and therefore these cultivars may be useful for regions subject to freezes.

All the chilling requirement models had high correlation coefficients with flowering date in three consecutive years (Table 3), which indicated that chilling requirement played an important role in the flowering of

Japanese apricot. A limited correlation coefficient between flowering date and heat requirement was observed (Table 3).

Discussion

Chilling accumulation in the field. In our study, the variability of chilling accumulation was very high when the Utah model was used (Table 1), which may be the result of the mild winter climate of Nanjing. Meanwhile, the high temperature registered in the late fall and early winter of 2011–2012 delayed the onset of chilling accumulation compared with the other two years (Table 1). The variability between years is similar with both the Weinberger model and dynamic model, which show lower variability than the Utah model. The dynamic model, as a result of its convincing theoretical framework and its application in both cool and warm areas, has proven to be a most appropriate method to determine

the chilling requirements of deciduous fruit. Therefore, we applied the dynamic model to measure chilling requirements or total chilling accumulation for selecting the appropriate cultivar in Nanjing.

Chilling requirements for breaking of dormancy of Japanese apricot cultivars. Researchers have used different methods to determine the chilling requirements of Japanese apricot. Ou and Chen (2003) in Taiwan used a Taiwan low-chill model with a range of −12 to 50 chill units. Wang et al. (2007) suggested that the 0 to 14 °C model could be used as an index for estimating chilling requirements in the southern subtropical area of China with the value from 110 h to 180.3 h. Yamane et al. (2006) applied the 0 to 7.2 °C model and reported that the early flowering cultivar Ellching required 300 chilling hours, whereas the midseason flowering cultivar Nanko required 500 h. Comparing results obtained by different researchers is difficult because many factors need to be considered such as the choice of plant material, the criteria used to determine when dormancy is completed, and the environmental conditions during the previous growing season (Dennis, 2003). Another important factor is the lack of standard protocols to calculate chilling requirements, which hinders the comparison of the chilling requirements. When chilling requirements are supplemented with information on tree behavior as well as the location, conditions, and duration under which the chilling requirements were determined, they will have a broader application (Campoy et al., 2010, 2011). Some researchers began to dedicate to the conversion factors, which facilitated the comparison of chilling requirements calculated with different chilling models and different areas (Luedeling et al., 2009b).

Others researchers also reported a high correlation between chilling requirement and flowering time (Campoy et al., 2012; Ruiz et al., 2007). In agreement with our results, there is also a high correlation between chilling requirement and flowering time with

Table 4. Heat requirements for flowering of Japanese apricot cultivars (2009–12).^z

Cultivar	Yr	Breaking dormancy	Flowering (F ₅₀)	Delta JD				GDH			
				Value	Mean ^y	SD	CV (%)	Value	Mean	SD	CV (%)
Taoxingmei	2009–10	5 Jan.	12 Feb.	38				1332			
	2010–11	29 Dec.	17 Feb.	50	456 b	6.7	14.7	992	1103	198.7	18
	2011–12	30 Dec.	17 Feb.	49				983			
Shuangshuidaroumei	2009–10	25 Dec.	5 Feb.	42				1269			
	2010–11	22 Dec.	12 Feb.	52	46 b	5.1	10.7	1288	1235	76.6	6.2
	2011–12	23 Dec.	10 Feb.	49				1147			
Dongqing	2009–10	10 Feb.	12 Mar.	30				1168			
	2010–11	11 Feb.	5 Mar.	22	29 ab	6.6	22.8	1059	1018	174.4	17.1
	2011–12	31 Jan.	7 Mar.	35				827			
Xiyeqing	2009–10	24 Feb.	1 Mar.	8				1400			
	2010–11	18 Feb.	7 Mar.	17	20 a	13.7	68.5	1196	1179	230.3	19.5
	2011–12	5 Feb.	12 Mar.	35				940			
Fenghou	2009–10	8 Mar.	19 Mar.	17				1635			
	2010–11	4 Mar.	18 Mar.	14	17 a	3.5	20.2	1870	1697	151.3	8.9
	2011–12	28 Feb.	21 Mar.	21				1587			
Yanhua	2009–10	8 Mar.	17 Mar.	9				1156			
	2010–11	25 Feb.	13 Mar.	16	16 a	6.5	41.4	1494	1250	213.1	17.1
	2011–12	21 Feb.	15 Mar.	22				1100			

^zThe date of dormancy breaking and flowering (F₅₀) also presented in this table. The delta JD was calculated in this table.

^yWithin columns, different letters (a and b) indicate statistically significant differences among cultivars by Duncan's multiple range test at 5% level.

JD = Julian days; GDH = growing degree-hours.

R close to 0.98. Therefore, we can classify the Japanese apricot cultivars by flowering time. Our results showed a high correlation between chilling requirement and date of dormancy breaking, which agrees with the data of Campoy et al. (2012).

Heat requirements for flowering of Japanese apricot cultivars. The results showed that the difference in heat requirements of different cultivars for flowering, and of the same cultivar in different years, was not significant. Many researchers had reported this phenomenon in almond [*Prunus dulcis* (Mill.) D.A. Webb] (Egea et al., 2003), apricot (*Prunus armeniaca* L.) (Ruiz et al., 2007), sweet cherry (*Prunus avium* L.) (Alburquerque et al., 2008), and pistachio (*Pistacia vera* L.) (Rahemi and Pakkish, 2009). The results obtained in apricot by Bailey et al. (1982) and Guerriero et al. (2002) did not show a correlation between chilling requirements and heat requirements. Linsley-Noakes and Allan (1994) and Egea et al. (2003) found no differences in heat requirements with different chilling requirements with nectarine and almond cultivars. Swartz and Powell (1981) observed in apple [*Malus domestica* (Borkh)] cultivars that chilling requirements were positively correlated with heat requirements for flowering. A high negative correlation between chilling requirements and heat requirements in peach (*Prunus persica*) was reported by Chen et al. (2012) and Pawasut et al. (2004), which indicated that heat requirement is dependent on the amount of chilling exposure with reduced heat requirement after a long chilling exposure. A low negative correlation between chilling requirements and heat requirements has been reported by many authors (Alburquerque et al., 2008; Campoy et al., 2012; Egea et al., 2003; Ruiz et al., 2007), but our results show a positive correlation between chilling requirements and heat requirements. These contradictory results may be explained by different climatic conditions, especially temperature.

Many researchers who studied the relations among chilling requirements, heat requirements,

and flowering date obtained different results. An inverse relationship between the effects of chilling and heat requirements on the flowering date of peach cultivars was found (Citadin et al., 2001). Alonso et al. (2005) reported that heat requirements of almond were more important for regulation of flowering date than chilling requirements in the cold climatic conditions of Zaragoza (northeast Spain). However, in southeast Spain, the flowering date of some almond cultivars was influenced more by chilling than by heat requirements (Egea et al., 2003). Campoy et al. (2012) and Ruiz et al. (2007) reported similar results, which indicates that flowering date is only slightly influenced by heat requirements and that other factors are more important, especially chilling requirements. Our results support this limited relationship between flowering date and heat requirements, which indicates that other factors are responsible for variation of the flowering date.

Flowering date of Japanese apricot cultivars. A wide range in the flowering date (F₅₀) from 5 Feb. to 21 Mar. was observed in all three years and was associated with the higher temperatures recorded. A low negative correlation between delta DJ and flowering date was reported by Campoy et al. (2012). However, our results showed a high negative correlation between delta DJ and flowering date and cultivars with lower chilling requirements showed earlier flowering dates. In our study, no significant differences were found between years with regard to the flowering dates; for example, 'Fenghou' flowered at approximately the same time in all three years. Many authors have reported no significant differences among heat requirements of cultivars, and flowering dates of cultivars, but a significant correlation was found between chilling requirement and flowering dates (Campoy et al., 2012; Egea et al., 2003; Ruiz et al., 2007). Our results suggested that the chilling requirement is the main factor determining the flowering date.

Conclusions

The dynamic model has a lower CV than the Utah and the Weinberger models in three successive studied years. As a result of its convincing theoretical framework and wide application, we recommend it to quantify chilling requirements of Japanese apricot under warm climatic conditions such as in Nanjing. However, more complex and more accurate models are needed to open new avenues in better understanding the complex process of dormancy.

The range of chilling requirements of the cultivars studied was from 26.3 to 75.7 chilling portions, and the heat requirements varied from 1017.7 GDH to 1697.3 GDH. However, our results do not clarify whether the heat requirements for flowering are an intrinsic characteristic of the cultivar.

The results show a high positive correlation between chilling requirements and flowering date. The relationship between heat requirements and flowering date was also positive, although the correlation coefficient was quite low. A positive correlation was observed between chilling requirements for breaking of dormancy and heat requirements for flowering. In addition, there is a high negative correlation between chilling requirements and delta JD and a low negative correlation between heat requirements and delta JD. These parameters are very useful in agricultural productions and scientific researches. Therefore, further work is needed to estimate the chilling and heat requirements of more Japanese apricot cultivars to complete our knowledge of the adaptability of this species to areas where its culture has not been traditional.

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