Among-station Analysis of Thermal and Solar-thermal Phenological Models for Flowering of *Syringa vulgaris*

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Abstract. The within-station performance of the most accurate phenological model in each of three classes of hourly models was compared for the ability to predict flowering dates of common purple lilac (*Syringa vulgaris* L.). For the three model classes used, day-only, solar thermal unit (STU), and 24-hour interpolations were made between three threshold temperatures and five effective temperature exponents. The most accurate within-station model for each of the three model classes, all having a threshold temperature of 5C, were: $(T - 5)^{1.54}$ day-only, $(T - 5)^{1.26} R^{0.5}$ STU, and $(T - 5)^{1.70}$ 24-hour, where T = temperature and R = solar radiation. These three models and the corresponding three linear temperature exponent models were then compared for among-station performance using 10 sites in the western United States. The most accurate model for the among-station analyses was the $(T - 5)^{1.0}$ day-only model. The two STU models did not perform as well as the two day-only and the two 24-hour models.

There is a need for improved plant phenological models for incorporation into comprehensive plant growth models (Daughtry et al., 1984; Fuchigami and Nee, 1987; Leith, 1974). While degree-day models are commonly used, they often fail when applied in climatic areas that differ significantly from the locations where they were developed. A common reason for failure is the lack of long-term hourly meteorological and concomitant plant phenophase information. Some investigators, realizing the deficiencies of the degree-day method, have used procedures to estimate 24-h temperature cycles (Heuer et al., 1978; Lindsey and Newman, 1956; Richardson et al., 1974).

In our study, the among-station performance of linear and nonlinear thermal and solar-thermal models were compared using 20 years of data on the phenology of the common purple lilac at 10 locations in the western United States and hourly records of temperature and solar radiation. Flowering dates were correlated in a previous within-station study with accumulated hourly DU from 1 Jan. to 7 days before the earliest recorded flowering date at each location (Caprio and Snyder, 1989). The flowering date phenophase is defined as the time when the first flower in any of the flower clusters (panicles) is fully open. The data analyzed in the previous study were for the period 1956-1976 at seven locations in the northern part of the western United States.

One hundred twenty-five models were compared in the previous within-station study using arbitrarily selected temperature thresholds of - 0.6C, 2.2C, and 5C and effective temperature and/or solar radiation raised to the 0.5, 1.0, 1.6, 2.0, and 2.4 power (Caprio and Snyder, 1989). The models consisted of day-only models, night-only models, 24-h models, solar-only models, and STU models.

The threshold temperature refers to that temperature above which DU begin. Thus, if the temperature of a given hour is

11C and the threshold temperature is 5C, the hour has an effective temperature of 6C. If the exponent of that effective temperature is 1.0, the DU for that hour is 6. If the exponent of that effective temperature is 1.6, the DU for that hour is 6 to the 1.6 power or 17.6. Day-only models are those in which DU are counted only during daylight hours. Night-only models are those in which DU are counted only during nighttime hours. DU are counted during all 24 h in 24-h models. Solar-only models consider only total hourly solar radiation. STU models consist of the product of hourly effective temperature taken to its exponent multiplied by hourly solar radiation taken to its exponent.

In a previous study (Caprio and Snyder, 1989), the model classes night-only and solar-only had lower average correlations and were less accurate than the other three model classes. Models that used - 0.6C as the threshold temperature yielded lower correlations than models that used 2.2C or 5.0C.

An objective of this study was to determine, by interpolation, the precise temperature exponents that would yield the highest correlations for each of the three model classes that were most accurate in the previous within-station study (Caprio and Snyder, 1989). A second objective was to determine the among-station performance of the three models that proved to be most accurate in this within-station analysis and also to determine the among-station performance of the linear counterparts of these three most accurate models. The procedure for determining the annual flowering dates at all sites in this study is described by Caprio and Snyder (1989).

Materials and Methods

Within-station analysis. Before undertaking the among-station analysis in this study, an effort was made to estimate the temperature exponent that would yield the highest correlation for each of the three most accurate within-station model classes as previously determined (Caprio and Snyder, 1989) and using data from the same seven stations in that study. The correlation for each of the seven stations was between each year's date of first flower and the corresponding year's accumulated DU from 1 Jan. to 7 days before the earliest recorded date of first flowering at each station. This estimation was accomplished by plot-

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Abbreviations: DU, developmental units; STU, solar thermal units.

ting an average of the correlations of the seven stations (Caprio and Snyder, 1989) on the abscissa and effective temperature exponents on the ordinate for each of the three model classes for thresholds of 2.2 and 5C (Fig. 1). Highest correlations and the associated effective temperature exponents were determined from smooth curves drawn by eye through the plotted points. The -0.6C threshold was not included in Fig. 1 because the average correlations did not reach a maximum within the range of exponents of effective temperatures that were tested. The meteorological data for both the previous and the present study were taken from SOLMET magnetic data tapes for both hourly temperature (T) and hourly global solar radiation (R, in units of $\text{kJ}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) (National Climatic Data Center, 1978). Tem-

peratures > 25C were considered to be the same as 25C when accumulating DU in the various models.

Among-station analyses. The coefficient of variation (cv) method was used to make among-station model comparisons of DU accumulations (Arnold, 1959). Hourly DU for the 10 stations listed in Table 1 were accumulated each year from 1 Jan. to the date of first flowering of each year, and the means of the accumulated DU of each station were tested by the cv method. Temperatures > 25C in this analysis were considered the same as 25C when accumulating DU in the various models.

For Cheyenne, Wyo., hourly accumulations were begun on 1 Feb. rather than 1 Jan. because of the late date at which the growing season begins. Accumulated DU for Sacramento, Calif.,

Fig. 1. Curves drawn by eye showing the relation between exponents of effective temperature and correlation coefficients (in parentheses) for three model classes with threshold temperatures of 2.2C (left) or 5C (right). A horizontal bar is drawn through the point on the curve where the correlation is highest.

Table 1. Geographical and phenological information on locations for which correlations were made between hourly records of temperature and solar radiation and historical flowering dates of the lilac.

Station	Latitude (N)	Longitude (W)	Elevation (m)	Flowering date		Period of record	No. of correlation years
				Earliest	Average		
Albuquerque, N.M.	35° 03'	106° 37'	1623	26 Mar.	19 Apr.	1957-80	20
Boise, Idaho	43° 34'	116° 13'	865	15 Apr.	28 Apr.	1957-80	20
Cheyenne, Wyo.	41° 49'	104° 49'	1867	11 May	23 May	1957-80	20
Denver, Colo.	39° 46'	104° 53'	1610	23 Apr.	8 May	1957-80	20
Glasgow, Mont.	48° 13'	106° 37'	694	30 Apr.	18 May	1956-79	21
Great Falls, Mont.	47° 29'	111° 21'	1116	2 May	15 May	1956-79	19
Medford, Ore.	42° 22'	122° 52'	396	29 Mar.	13 Apr.	1957-80	19
Sacramento, Calif.	38° 31'	121° 30'	5	6 Mar.	22 Mar.	1957-80	20
Salt Lake City, Utah	40° 46'	111° 58'	1287	17 Apr.	29 Apr.	1957-80	20
Seattle-Tacoma, Wash.	47° 27'	122° 18'	118	18 Apr.	30 Apr.	1957-80	20

were started on 2 Feb. rather than 1 Jan. since it was determined that this starting date yielded higher correlations between accumulated growth units and date of bloom. The higher correlations at Sacramento with the 2 Feb. starting date may be attributable to lateness in the completion of rest that requires a minimum accumulation of low temperatures before the plant can develop in response to early season warming (Ashcroft et al., 1977). The total hourly DU accumulated from 1 Jan. to flowering date at each location for each year were averaged for each of the six models at each location to obtain a mean station accumulation of DU for each model (Table 2). More DU were accumulated before the flowering date for Cheyenne, Denver, and for Albuquerque, N.M., than for the other seven locations (Table 2). The greater number of DU at these locations compared with the seven other locations were converted to "days later than the expected flowering dates" of 8, 14, and 13 days, respectively. These three locations were treated as a separate group because of this large difference in the numbers of required accumulated DU for flowering.

The among-station comparison of the performance of each of the six models was then based on the cv of the 20-year mean accumulation of DU for each of the seven stations. The three models shown in the lower portion of Table 3 were chosen for among-station comparison—all with base temperature of 5C. These three models were selected because of their high corre-

lations in the within-station analyses. Linear temperature exponent versions of these three models were also tested by the cv method for among-station ranking. We chose linear models because they are widely used in degree-hour models.

Results

Within-station analyses. The correlation coefficient method was applied for within-station model testing in the previous study (Caprio and Snyder, 1989), which was an appropriate procedure because the DU accumulated at a given station terminated on the same date each year. The points where the curves extended farthest to the right (Fig. 1) was taken as the highest average correlation, and the associated effective temperature exponent was read on the ordinate (Table 4). A solar radiation exponent of 0.5 was used in this approach because it provided the most accurate models compared with the other solar radiation exponents tested. For each of the three model classes in Fig. 1, the 5C threshold temperature models reached their maximum correlation at lower exponents of effective temperature than the 2.2C threshold temperature models.

Since correlations of corresponding models tended to be slightly higher for a threshold temperature of 5C than 2.2C (Table 3), 5C was selected for further study.

The exponent of effective temperature that had the highest correlation coefficient was determined for each of the curves

Table 2. Mean accumulated developmental units at 10 locations from 1 Jan.^z to lilac flowering dates for six models.

Location	Day-only (T - 5) ^{1.54} × 10 ³	STU ^y (T - 5) ^{1.26} R ^{0.5} × 10 ⁶	24-h (T - 5) ^{1.70} × 10 ³	Day-only (T - 5) ^{1.0} × 10 ³	STU ^y (T - 5) ^{1.0} R ^{0.5} × 10 ⁶	24-h (T - 5) ^{1.0} × 10 ³
Boise, Idaho	13.41	8.81	25.25	4.23	5.05	5.97
Glasgow, Mont.	16.21	10.52	28.37	4.58	5.70	5.76
Great Falls, Mont.	16.04	10.01	28.26	4.82	5.58	6.22
Medford, Ore.	13.85	7.93	24.88	4.50	4.58	6.17
Sacramento, Calif. ^z	13.71	8.07	28.92	4.06	4.47	6.61
Salt Lake City, Utah	14.85	10.31	26.94	4.47	5.77	6.00
Seattle, Wash.	13.49	7.60	25.06	4.94	4.61	7.31
Mean	14.51	9.04	26.81	4.51	5.11	6.29
cv	8.3	13.6	6.5	6.8	11.2	8.3
Albuquerque, N.M.	23.32	15.26	43.01	6.53	8.26	8.67
Cheyenne, Wyo. ^z	19.24	13.11	32.17	5.65	7.26	6.80
Denver, Colo.	21.53	14.35	37.42	6.16	7.85	7.68
Mean	21.36	14.24	37.53	6.11	7.79	7.72
cv	9.6	7.6	14.5	7.3	6.5	12.1

^zAccumulations start on 1 Feb. for Cheyenne and 2 Feb. for Sacramento.

^yUnits are kilojoules per square meter - degrees Celsius - hours (kJ·m⁻² - C - h).

Table 3. Estimated effective temperature exponent that had the highest correlation for each of three model classes for threshold temperatures of 2.2 and 5C. (Based on data from seven locations analyzed in the previous study.)

Model class	Threshold temperature (°C)	Effective temperature exponent	Average correlation	Solar radiation exponent
Day-only	2.2	2.06	-0.658	---
STU	2.2	1.75	-0.652	0.5
24-h	2.2	2.26	-0.648	---
Day-only	5	1.54	-0.658	---
STU	5	1.26	-0.656	0.5
24-h	5	1.70	-0.649	---

Table 4. Equation-derived threshold temperature for each of the three model classes that, would yield the highest correlation for an effective temperature exponent of 1.6.

Model class	Threshold temperature (°C)	Effective temperature exponent	Average correlation	Solar radiation exponent
Day-only	4.69	1.6	-0.659	---
STU	3.07	1.6	-0.653	0.5
24-h	5.49	1.6	-0.649	---

Fig. 2. Lines for each of three model classes indicating effective temperature exponent-threshold temperature combinations that yield the highest correlations (based on points at threshold temperatures of 2.2 and 5C).

(Fig. 1, Table 3). The six exponents were plotted for each of the three model classes for the threshold temperatures of 2.2C and 5C (Fig. 2). A straight line was drawn through the two points for each of the three model classes and the mathematical equations of these lines were derived. The equations indicate

the threshold temperature, y , in degrees Celsius, for each of the three classes of models that yields the highest average correlation for any given exponent of effective temperature (x).

Along a given line in Fig. 2, the correlation coefficients change only slightly. If linear extensions of these lines are associated with similar small changes in correlation coefficients, it might be expected that smaller effective temperature exponents would provide only slightly higher correlations. The equations (Fig. 2) can be used to determine which threshold temperatures are most appropriate, in conjunction with linear exponents of effective temperature. Since the points are beyond the 5C threshold temperature, estimates of average correlations were not attempted. However, projected threshold temperatures using Fig. 2 for linear day-only, STU, and 24-h models were 7.9, 6.4, and 8.5C, respectively. These threshold temperatures for growing degree-hour summations are higher than reported for middle latitude perennial plants that normally bloom in the spring (Ashcroft et al., 1977; Brown, 1953; White, 1979) and were not considered further in this study.

To illustrate the use of the equations in Fig. 2, suppose a constant effective temperature exponent of 1.6 for all three models is selected for application, then the equations can be used to determine the threshold temperature that yields the highest average correlation for each of the three classes of models (Table 4). Corresponding threshold temperatures in the previous study (Caprio and Snyder, 1989) for the day-only, STU, and 24-h models with effective temperature exponents of 1.6, were 5.0, 2.2, and 5.0C, respectively, and the model correlations are essentially the same. Thus, the equations that produced the highest correlations in this example yield threshold temperatures that are in close agreement with those of the previous study using a 1.6 exponent of effective temperature.

Any of the models presented in this study that do not differ significantly from each other may be equally valid. However, those models with highest average correlations are most likely to yield the more accurate results.

Among-station analysis. For the seven-station group, mean DU vary from a low of 4514 for the $(T - 5)^{1.0}$ day-only model to a high of 26,811 for the $(T - 5)^{1.70}$ 24-h model (Table 2). The cv for the seven-station group varies from a low of 6.5 for the $(T - 5)^{1.70}$ 24-h model to a high of 13.6 for the $(T - 5)^{1.26} R^{0.5}$ STU model, where T is in C and R in $\text{kJ}\cdot\text{m}^{-2}$. The $(T - 5)^{1.0}$ day-only model also had a relatively low cv value of 6.8. High cv values of STU models for accumulated DU indicate that these models did not perform as well as the day-only and 24-h models.

Mean model values of accumulated DU for the three-station group were considerably larger than for the seven-station group for all six models. Coefficients of variation for the three-station group, however, did not differ markedly from those of the seven-station group, which tends to confirm the unity of each group as separate entities.

The means of the within-station correlations for the six models indicate that the linear models performed as well as the nonlinear and that all of the models account for $\approx 60\%$ of the year-to-year within-station variation in flowering dates (Table 5). While correlations for all of these actual vs. predicted flowering dates are higher than in the previous study in which DU were accumulated from 1 Jan. to 7 days before the earliest recorded flowering date at each location, the ranked order of the correlations of the various models remained the same.

Within the seven-station group, the differences in the means of the correlations for the six models (Table 5) were small,

Table 5. Correlations between actual and predicted flowering dates for six hourly phenological models at 10 locations.

Location	Day-only ($T - 5$) ^{1.54}	STU ($T - 5$) ^{1.26} R ^{0.5}	24-h ($T - 5$) ^{1.70}	Day-only ($T - 5$) ^{1.0}	STU ($T - 5$) ^{1.0} R ^{0.5}	24-h ($T - 5$) ^{1.0}
Boise, Idaho	-0.81	-0.83	-0.78	-0.77	-0.83	-0.74
Glasgow, Mont.	-0.87	-0.88	-0.81	-0.86	-0.88	-0.83
Great Falls, Mont.	-0.73	-0.72	-0.76	-0.73	-0.73	-0.75
Medford, Ore.	-0.94	-0.92	-0.94	-0.94	-0.91	-0.93
Sacramento, Calif. ^z	-0.64	-0.59	-0.63	-0.67	-0.61	-0.57
Salt Lake City, Utah	-0.83	-0.85	-0.85	-0.80	-0.83	-0.79
Seattle, Wash.	-0.67	-0.61	-0.59	-0.76	-0.65	-0.70
Mean	-0.79	-0.77	-0.76	-0.79	-0.77	-0.76
cv	13.9	17.0	16.2	11.1	15.0	14.8
Albuquerque, N.M.	-0.75	-0.75	-0.77	-0.68	-0.72	-0.74
Cheyenne, Wyo. ^z	-0.91	-0.92	-0.90	-0.93	-0.94	-0.93
Denver, Colo.	-0.69	-0.69	-0.73	-0.62	-0.67	-0.63
Mean	-0.78	-0.79	-0.80	-0.74	-0.77	-0.77
cv	14.9	15.1	10.9	22.4	18.5	19.7

^zAccumulations start on 1 Feb. for Cheyenne and 2 Feb. for Sacramento.

ranging from a high of 0.79 for the two day-only models to a low of 0.76 for the two 24-h models. Differences in cv values of the correlations of the seven-station group were highly variable, ranging from a low of 11.1 for the ($T - 5$)^{1.0} day-only model to a high of 17.0 for the ($T - 5$)^{1.26}R^{0.5} STU model. The most accurate of the six models was the ($T - 5$)^{1.0} day-only model as indicated by its high correlation (0.79) and its low cv value (11.1).

Differences, in mean correlations of the three-station group were also relatively small. The cv values tended to run higher than for the seven-station group, but this was not considered a valid comparison because of the few stations in the smaller set.

Discussion

Within-station analyses. The models of the day-only model class generally had higher average within-station correlations than the models of the 24-h and STU model classes (Caprio and Snyder, 1989). Photoperiod likely is not be a contributing factor since the correlations were between annual date of flowering and the annual accumulation of DU for each station for the same time period, i.e., from 1 Jan. to 7 days before the earliest flowering date at each location. The higher average correlations of the day-only models than of the 24-h models may be explained by the yearly phenological anomaly determinations for each station that were based on the pattern of flowering date anomalies in the vicinity of the stations, rather than on observations at the specific sites. Daytime temperatures tend to be spatially less variable over the landscape than nighttime temperatures (Caprio, 1961). Thus, isotherms on a map (or phenological isophanes) are more likely to parallel daytime than 24-h averages of temperature. However, the higher correlations of the day-only models compared with the 24-h models may simply relate to the fact that nighttime temperatures are not included in the day-only models.

Day-only models ranked higher than the STU model, which may be attributable to the greater error usually inherent in solar radiation records compared with the more precise temperature measurements (Titus and Truhlar, 1969).

The STU models were more accurate than the 24-h models (Caprio and Snyder, 1989). Ambient temperatures of the buds and leaves exposed directly to the sun tend to be higher than the thermometer readings in the shelter on sunny days. The STU

models would account for this interaction between solar radiation and bud temperature.

These results, in which degree-hour models (those without solar radiation) are the highest ranked of the models, differ from a previous study (Caprio, 1974) where the daily STU method (effective mean *daily* temperature $\times$ total *daily* global solar radiation) was superior in testing to the growing degree-day method. This difference may be related to the comparison of two locations with the same mean daily temperature (the mean of the lowest and highest temperature). The location with more solar radiation usually has a greater diurnal temperature range and more degree-hours for each degree-day. Interacting solar radiation with mean daily temperature may have compensated partially for the effect of the variations in diurnal temperature range. The degree-day method does not adequately reflect the sequence of temperatures to which plants are exposed over a 24-h period. Thus, phenological models that consider only degree-days are not likely to apply over extensive geographic areas characterized by large differences in diurnal temperature ranges. Use of hourly temperatures rather than daily maximum and minimum temperatures should provide improved results in phenological modeling.

Among-station analyses. We do not know the basis for the higher DU requirement at the three highest elevation sites (Cheyenne, Denver, and Albuquerque) than at the other seven locations.

These results, based on the seven-station group, indicate that linear temperature forms of the hourly day-only, STU, and 24-h models perform as well as the nonlinear temperature models and that the ($T - 5$)^{1.0} day-only model was the most accurate model. Although the cv of accumulated units of the ($T - 5$)^{1.70} 24-h model was slightly lower than that for the ($T - 5$)^{1.0} day-only model (Table 2), its low within-station correlation and high cv of the correlation (Table 5) indicate that it did not perform as well as the ($T - 5$)^{1.0} day-only model for both within- and among-station applications.

While the most accurate threshold temperature for *degree-day* models of the common purple lilac appears to be -0.6C (Caprio, 1974), the most accurate threshold temperature for *degree-hour* models of the lilac in these studies is 5C. These results are in agreement with those of White (1979) who studied the flowering dates of 53 plant species in northeastern Montana over 4 years using both degree-day and degree-hour models. He

also found that the most accurate threshold temperatures for degree-hour models were higher than for degree-day models.

Early season lilac development is predominantly responsive to temperatures during daylight hours. Phenological modeling of plants typically takes into account hourly temperatures during the entire 24-h period. The results of this study suggest that accumulation of hourly units during daylight hours only (day-only models), may help to realize more accurate phenological models for early season plant development.

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