A Model to Predict Peach Phenology and Maturity Using Meteorological Variables

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Additional index words. *Prunus persica*, modeling weather effects

Abstract. This paper outlines the development of regional-scale peach [*Prunus persica* (L.) Batsch] phenology models for the southeastern United States. We constructed regression-based models to predict full bloom and first harvest using phenological data for eight peach cultivars grown in Georgia, South Carolina, and Texas and meteorological data from nearby cooperative weather stations. The mean absolute error (MAE, absolute value of predicted date minus observed date) of the all-cultivar full bloom model was 3.48 days. Bloom model errors were roughly 6 to 7 days (or less) 90% of the time, while comparable natural bloom date variability at a single station is about 12 to 13 days. Only two cultivars ('Dixired' and 'Elberta') had first harvest models with 90% error thresholds at or less than the natural harvest date variability at a single station (9 to 10 days). Thus, first harvest appears to be less predictable than full bloom, at least in terms of the temperature variables used in this study. The bloom model could serve as a prognostic tool, while the two cultivar harvest models are appropriate only for diagnostic studies, such as evaluating the potential response of a peach cultivar in a new location. The appeal of the models is that they consider numerous cultivars over a wide region and they use readily available meteorological data.

Peach growers in the southeastern United States, like those in other regions, face risks related to market forces and climate variability. Peach phenology models, used to predict the development stages of typical peach culti-

vars, help growers address these risks. Phenological models serve three specific needs: 1) They provide growers with a relatively complete assessment of how particular cultivars fare under current conditions, which facilitates cultivar choice (Savage and Prince, 1972; Weinberger, 1950). 2) By informing growers of the stage of phenological development during a growing season, phenological models can indicate whether frost protection is needed. If, for example, a cultivar's chilling requirement has been satisfied early in the winter season, trees can be treated with dormant oil during late winter warm periods to delay dehardening and bloom and reduce the threat of subsequent frost damage (Call and Seeley, 1989; Deyton et al., 1992; Myers et al., 1996). 3) If effective, models more accurately and consistently predict maturity dates than event history (interannual variability of phenology dates at a site), which improves the market delivery of peaches (Smith, 1985). Reasonably accurate peach maturity models can also help researchers assess the effects of various climate change possibilities on peach production in the Southeast. The models provide a framework for evaluating the dual effects of changes in winter chilling accumulation and changes in the

last -2.2°C spring frost date (Carbone and Schwartz, 1993).

Because peach trees require a period of rest at low temperatures (chilling) before they respond to warm weather in the spring (Weinberger, 1967), a phenological model for peaches must first evaluate the chilling requirement of a selected cultivar and then advance the plant through physiological growth stages to fruit maturity. Researchers have developed a range of methods to express the relationship between meteorological variables and these two fundamental stages.

Chilling requirement can be measured simply by determining the accumulated hours below a temperature threshold (commonly between 6 to 7.2°C), but research has determined that chilling in some temperature ranges is more effective than others and, perhaps more importantly, that subsequent higher temperatures can in some cases negate earlier chilling (Erez and Lavee, 1971). Accounting for this phenomenon, the "Utah method" assigns variable weights to differing temperature ranges, resulting in "chill units" (Ashcroft et al., 1977; Lombard and Richardson, 1979; Richardson et al., 1974). While the method has been widely used, standard chill unit requirements have not been determined for most peach cultivars. Several researchers also have noted that chill units still do not account adequately for anomalously high temperatures (typically >21 – 23°C) and, hence, overestimate the chilling accumulation in regions with mild winters, such as the Southeast (Erez et al., 1979; Shaltout and Unrath, 1983). Harker et al. (1994) proposed and tested a method that accounts for high temperatures in the period immediately following 1 Oct., the conventional start date for chilling accumulation (Linville, 1990). This "Auburn method" adjusts the chilling start date each year such that chill accumulation begins only after 50 positive chill units are recorded over a 10-consecutive-day period after 1 Oct. The chilling start date is set to the day when the first positive chill unit occurs after the highest negative unit during the 10 days. Further, Couvillon and Erez (1985) found that chilling negation does not occur when at least three-fourths of the chilling requirement has been satisfied before exposure to temperatures $\geq 23^{\circ}\text{C}$.

Physiological development after the chilling requirement has been satisfied is usually measured in terms of heat accumulation above a threshold temperature, calculated either as growing degree-days or growing degree-hours (GDH). The operative threshold or "base" temperature for peaches can range from 0 to 10°C , but is most commonly 4.4°C (Richardson et al., 1974). Because the hourly temperature data necessary to calculate heat or chill units precisely are not widely available, they are commonly approximated from the area under a sine curve fit to the daily maximum–minimum temperatures (Arnold, 1960; Baskerville and Emin, 1969) and may also incorporate a separate cooling curve to determine nighttime temperature changes (Linville, 1990). However, Smith's (1985) peach maturity model employs a simpler

Received for publication 30 May 1996. Accepted for publication 23 Oct. 1996. This research was funded by the Southeast Regional Climate Center, NOAA Grant No. NA26CPO329-03. We also thank D.H. Byrne (Texas A&M, College Station), J. Haun, W.C. Newall, J. Ross, and S. Scott (Clemson Univ., Clemson, S.C.) for data contributions; M. Braun (Univ. of South Carolina, Columbia), D.R. Ouellette (Clemson Univ.), R. Ghose, and G.J. Lennartson (Univ. of Wisconsin–Milwaukee) for data compiling, editing, and analysis; and D. Linville (Clemson Univ.), R. Marini (Blacksburg, Va.), D.J. Smith (Southeast Regional Climate Center, Columbia, S.C.), and C.J. Willmott (Univ. of Delaware, Newark), and two anonymous reviewers for helpful comments and suggestions. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked *advertisement* solely to indicate this fact.

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method of computing degree-days, requiring only mean daily temperature.

While researchers have modeled various aspects of peach phenological development (Haun and Coston, 1983; Scalabrelli and Couvillon, 1986; Smith, 1985; Werner et al., 1988) on a local scale, none have focused on developing regional peach maturity models. Yet, the meteorological data most widely available are derived from National Weather Service cooperative weather stations at this regional scale. Our study was undertaken to develop regional full bloom and first harvest peach models in the southeastern United States, incorporating results from prior modeling efforts, but using broadly available meteorological inputs.

Materials and Methods

Data. Full bloom and first harvest (i.e., when 10% of fruit are firm ripe) dates for peach cultivars at available orchard sites were collected from university, U.S. Dept. of Agriculture–Agricultural Research Service, agricultural industry, and private grower records. More than 1400 observations/locations were compiled for South Carolina. Additional data were added from other South Carolina sources and sources from Georgia and Texas. The data were selected to include eight cultivars, chosen because they had differing chilling requirements and had long observational records throughout the study region. Daily air maxima and minima were acquired from 12 meteorological stations in Georgia, South Carolina, and Texas (Table 1). Phenological data from eight peach cultivars were matched to temperature data at these stations to provide a consistent spatial and temporal record.

Basic data processing. A FORTRAN computer program (PEACHVAR) was written to process the daily maximum–minimum temperatures into chill hour and GDH accumulations during the periods before phenological dates. The program incorporates a subroutine improved by Linvill (1990) which uses a sine-curve approximation during the day and a separate cooling curve at night, together with day length, to calculate hourly temperatures. These hourly temperatures are converted into chill, GDH, and temperature range hour (number of hours spent in a specific temperature range) accumulations necessary for model building. A second program (PEACHDIF) was developed to evaluate model predictive ability with the original maximum–minimum temperature data arrays. The original daily temperature values were recorded in degrees Fahrenheit and all processing was conducted in those units. Thus, temperature values and ranges reported in this paper are rounded to the nearest one-tenth degree Celsius. The appropriate base temperature for GDH calculations was determined for each model situation using Arnold's (1959) linear x-intercept approach. This technique regresses the average temperature over the development period (time from chilling satisfaction until the phenological event—heating period, x) against the rate of development (100/length of development pe-

riod, y). When y is set to 0 (the x-intercept, approximating the temperature when development rate is zero), the resulting equation is solved for x, the base temperature.

Regression and phenological modeling. The standard regression procedure is designed to identify the statistical relationship between a dependent variable and a set of independent predictor variables at a particular time. In the case of phenological modeling, this time is usually associated with a specific phenological event. For example, we may regress GDH against the date of bloom. Such events are not fixed at a particular date, but vary from year to year and location to location with each unique daily temperature time series. Schwartz and Marotz (1986, 1988) introduced a procedure modifying the standard regression equation to account for varying dates of phenological events. Based on a simple transformation of the dependent and independent variables before multiple regression model building, the dependent variable for the equation is expressed as an arbitrary constant (1000) divided by the actual phenological date (expressed as day of the year, January 1st = 1). Independent variables (such as GDH accumulation at the time of the phenological event) are all divided by the phenological date. The equation takes the form:

$$\frac{1000}{\text{date}} = B_0 + \left(\frac{B_1 x_{11}}{\text{date}}\right) + \left(\frac{B_2 x_{12}}{\text{date}}\right) + \dots + \left(\frac{B_n x_{1n}}{\text{date}}\right) + e_i \quad [1]$$

where e_i = deviations from a best-fit linear regression line.

This transformation allows the multiple regression procedure to optimize the coefficients (B_{1-n}) since they are each "standardized" by the date of the phenological event.

Multiplying through by date, we create an equation that reaches a value of 1000 when the optimized GDH threshold is reached:

$$1000 + B_0 \times \text{date} + B_1 x_{11} + B_2 x_{12} + \dots + B_n x_{1n} + e_i \quad [2]$$

If this threshold is reached early in the season, a value of 1000 will also be reached early, indicating an early predicted date. This structure allows the use of an empirical predictive model that responds to the differing rates at which GDH values are accumulated, without relying on knowledge of the actual phenological date. Thus, the coefficients and regres-

sion constant determined from Eq. [1] can be assimilated into an equation form that is more efficient for error testing and subsequent operational prediction Eq. [2].

Model building procedure. We constructed all-cultivar full bloom models for the period from chilling satisfaction until the full bloom date. Chilling satisfaction was computed for both the conventional 1 Oct. chill approach and the Auburn method. Both used a GDH base temperature of 0.6 °C (Arnold, 1959) and published chill hour accumulations for each cultivar (Ridley et al., 1986). Preliminary model tests indicated that a combined cultivar model would be feasible for full bloom. By contrast, it was necessary to develop first harvest models (full bloom until first harvest date) for each cultivar.

We used SPSS software to develop multiple regression equations for bloom and harvest prediction (Norusis, 1993). Possible independent variables included GDH and the number of hours spent in unique 1.1 °C temperature ranges from -7.2 to 25.6 °C, while phenological date was the dependent variable. All variables were transformed as indicated above. A set of unrelated independent variables was selected by examining a correlation matrix of all predictor variables and inspecting the variance inflation factors and eigen values produced by the SPSS collinearity diagnostics option. A stepwise option was then used to select the most powerful predictor variables for each model based on adjusted R^2 change and variable significance. We also selected two dummy variables. One was related to state (Georgia, South Carolina, or Texas) to test for regional differences in the model relationships, the other to cultivar used in the all-cultivar bloom models to test for response differences that were specific to cultivar. Interaction terms between these dummy variables and the continuous variables were also computed, as well as quadratic terms for the continuous variables. We used the stepwise option with all of the above variables to develop the final model form, again using adjusted R^2 change and variable significance to determine the most powerful variables. The preliminary model was evaluated for influential cases by examining the unstandardized

Table 1. Meteorological stations providing maximum and minimum temperature data for model development.

Station location	North latitude	West longitude	Elevation (m)
Georgia			
Byron	32.67°	83.72°	149
Fort Valley	32.57°	83.87°	149
South Carolina			
Anderson	34.50°	82.72°	232
Clemson	34.68°	82.82°	250
Johnston	33.78°	81.85°	189
Pontiac	34.13°	80.87°	134
Spartanburg	34.90°	81.92°	186
Texas			
Bowie	33.57°	97.85°	340
College Station	30.53°	96.42°	96
Henderson	32.18°	94.80°	152
Stephenville	32.22°	94.18°	447
Yoakum	29.28°	97.13°	117

predicted values, standardized difference in fit values, and covariance ratios. Heteroscedasticity was measured by examining a plot of studentized residuals vs. standardized predicted values.

The above regression procedure was conducted twice for each model. The first pass was done to identify influential cases that may have been the result of bad data, largely transcription errors from the phenological data source. Such cases were deleted from each data base. The second pass was performed by randomly selecting half of the data base, insuring that model performance was based on an independent test.

Model error testing. Model errors were evaluated by computing mean absolute error (MAE, the average of the absolute value of predicted date minus observed date over all cases) and root mean square error (RMSE) in the independent data set. MAE is considered the most robust measure of overall predictive model performance (Willmott, 1982 and personal correspondence). The frequency distributions of MAE values were computed for each model to measure model performance more conservatively. We selected the 90th percentile error value to conform to decision-making procedures used by peach growers.

When models had several significant terms, each was tested with a separate program run to determine if it improved predictive ability as measured by MAE. (For example, a three-variable model form would be tested with a model using only the two most powerful variables of the three, to determine MAE improvement.) Significant variables that did not improve MAE were removed from the models and the regression coefficients recomputed.

Model baseline comparison. Ultimately, model evaluation should be made within the context of existing measures of variability, such as those provided by historical phenology data themselves. Because the data are not extensive enough at every site to make a regional evaluation of natural event variability, we examined variability among the two phenological events and eight cultivars at one station (Johnston, S.C.) with an extensive data record. Five of the eight cultivars ('Coronet', 'Dixired', 'Elberta', 'Redhaven', and 'Redskin') had at least 10 years of data, which was considered a minimum for this analysis. Evaluation of the data from these five cultivars produced quite consistent results. Full-bloom dates were within ± 12 –13 days of the mean date for the cultivar 90% of the time. First harvest dates showed less variability than bloom—within ± 9 –10 days of the mean date for the cultivar 90% of the time. We concluded that, to be useful for prediction, a full-bloom model must have 90% error threshold values appreciably better than 12 days, and first harvest models must have 90% error threshold values better than 9 days.

Results

None of the dummy variables, interaction variables, or quadratic term variables improved performance of either the full-bloom or first

harvest model. Both, the conventional (1 Oct. chill accumulation start) and Auburn method all-cultivar full-bloom models used GDH accumulation and accumulated hours spent in the 24.5–25.6 °C range as predictor variables (Table 2). About 5% of the cases were removed by the first pass of the model building procedure. Results presented here come from model validation against a randomly selected half of the original database. The conventional full-bloom model was about one-half day better on average than the Auburn method full-bloom model. The error levels were consistent over all cultivars and regions, both in terms of MAE (3–4 days) and approximate 90% error threshold levels (6–7 days), which is roughly

5 days less than the natural bloom date variability (12–13 days). A scatter plot of predicted vs. observed dates did not show strong biases in model prediction over most of the data range (Fig. 1). At the extremes, however, very early dates were slightly overpredicted and very late dates were slightly underpredicted.

In all cases, the results of the first harvest models were less notable than the full bloom models. Only two cultivars had predictive power at or less than the interannual variability (Table 3). The 'Dixired' model was roughly the same as the interannual variability of first harvest dates, while the 'Elberta' model was ≈ 2 days less.

Table 2. Regression coefficients and model performance of full bloom models.

Model parameters and performance	Model	
	Conventional 1 Oct. chill start	Auburn method
Regression constant (and α -level of least significant variable)	7.059 (0.0005)	8.286 (0.0005)
Regressor variables (and coefficients) ²	GDH (0.018) HRS _{24.5-25.6 °C} (3.158)	GDH (0.013) HRS _{24.5-25.6 °C} (4.240)
Number of cases (original/cleaned/halved)	320/302/151	320/304/152
Model mean absolute error (days)	3.48	3.93
Approximate 90% model error threshold (days)	6.5	7.5
Approximate 90% observed interannual variability (days)	12	12
R ²	0.51	0.43

²GDH = growing degree hours; HRS = number of hours in specified temperature range.

Fig. 1. Scatter plot of modeled vs. observed first bloom dates for all cultivars, over all years.

Discussion

Our results compare favorably with other models designed to predict full bloom and peach maturity dates (Logan et al., 1990; Smith, 1985). These findings are particularly encouraging given our effort to develop a *regional* maturity model. While many previous studies have constructed empirical models for small growing areas and a few selected cultivars, our models demonstrate that a more general approach is feasible. Developed with data over a large region and for a wide range of cultivars, it creates a useful tool for predicting regional-scale full bloom and to a lesser extent selected first harvest dates. Similarly, our use of meteorological data from nearby cooperative weather stations rather than orchards contributes to model error, but provides a technique that is more broadly applicable than models requiring detailed environmental inputs. No adjustments were made to account for the microclimatic conditions of individual orchards.

We did examine the slight date biases detected in the full-bloom model, and determined that day-length variations were a possible cause. A correction factor was applied to the predicted model dates based on day length, resulting in the elimination of much of the bias. This adjusted full-bloom model had an overall MAE of 3.25 days, and RMSE of 4.11 days, which represents a slight improvement. After a case-by-case analysis, we decided that the overall improvement was marginal. Almost two-thirds of the cases were predicted no better or were predicted worse (62%). Another quarter of the cases were only improved by 1 day (27%). Thus, only a small number of cases (11%) had substantial improvements in prediction (2 to 3 days). We conclude that the all-cultivar full-bloom model has power as a predictive model (i.e., error levels are sufficiently better than natural variability). Results from the two harvest models ('Dixired' and 'Elberta') are equal to or slightly better than natural variability, and are best reserved for diagnostic studies (such as evaluating peach response in an area without actual phenological data) rather than for prediction.

Our findings further suggest that the use of the Auburn method—a means of accounting for the potentially warm weather in the Southeast during fall—did not improve prediction of full bloom. It is possible that such high temperatures are not as disruptive to chill accumulation as thought previously. More

likely, the coarse link between field phenological data and meteorological station data may have obscured the role of these high autumn temperatures. The Auburn method has proven successful in studies for smaller geographic areas when high quality field data are available (Harker et al., 1994).

Given the importance of establishing a clear starting point for heat accumulation models, it is probable that our use of chill hours instead of chill units adds to model error. Knowledge of chill units for specific cultivars should improve modeling accuracy. Graphical methods, used in other studies (Guerriero et al., 1990), failed when applied to 'Elberta' peaches during our preliminary test of the technique in the Southeast. Because this graphical method relies on peach data gathered over a wide latitudinal range, the limited extent of available Southeast phenological data may have contributed to the failure.

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Table 3. Regression coefficients and model performance of first harvest models ('Dixired' and 'Elberta' cultivars).

Model parameters and performance	Cultivar	
	'Dixired'	'Elberta'
Regression constant (and α -level of least significant variable)	5.595 (0.0035)	4.597 (0.0021)
Regressor variables (and coefficients) ^a	HRS _{12.8-13.9 °C} (0.818)	HRS _{7.8-8.9 °C} (0.840)
Number of cases (original/cleaned/halved)	44/42/21	55/52/26
Model mean absolute error (days)	5.38	4.73
Approximate 90% error threshold (days)	9.5	7.5
Approximate 90% observed interannual variability (days)	9	9
R ²	0.34	0.30

^aGDH = growing degree hours; HRS = number of hours in specified temperature range.