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Carla Cesaraccio · Donatella Spano · Pierpaolo Duce
Richard L. Snyder

An improved model for determining degree-day values from daily temperature data

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Abstract Although using hourly weather data offers the greatest accuracy for estimating growing degree-day values, daily maximum and minimum temperature data are often used to estimate these values by approximating the diurnal temperature trends. This paper presents a new empirical model for estimating the hourly mean temperature. The model describes the diurnal variation using a sine function from the minimum temperature at sunrise until the maximum temperature is reached, another sine function from the maximum temperature until sunset, and a square-root function from then until sunrise the next morning. The model was developed and calibrated using several years of hourly data obtained from five automated weather stations located in California and representing a wide range of climate conditions. The model was tested against an additional data-set at each location. The temperature model gave good results, the root-mean-square error being less than 2.0 °C for most years and locations. The comparison with published models from the literature showed that the model was superior to the other methods. Hourly temperatures from the model were used to calculate degree-day values. A comparison between degree-day estimates determined from the model and those obtained other selected methods is presented. The results showed that the model had the best accuracy in general regardless of the season.

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C. Cesaraccio (✉) · P. Duce
Istituto per il Monitoraggio degli Agroecosistemi, CNR,
Via Funtana di Lu Colbu, 4A, 07100 Sassari, Italy
e-mail: cesaraccio@imaes.ss.cnr.it
Tel.: +39-079-268246, Fax: +39-079-268248

D. Spano
Dipartimento di Produzione Vegetale, Università della Basilicata, Potenza, Italy

R.L. Snyder
Department of Land, Air and Water Resources,
University of California, Davis, Calif., USA

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Introduction

In the literature, several models are presented describing the phenological response of a given species to temperature (Kramer et al. 2000). Although modeling approaches are different (Galán et al. 1998; Hänninen 1990; Kramer 1994; Maak and von Storch 1997), most models are based on temperature. In addition, air temperature is a fundamental input parameter for climatological and agricultural models (e.g. crop growth).

The number of days needed for the growth or phenological development of plant species and pests decreases at higher temperature. The development rate (1/time to develop) increases approximately linearly from a lower to an upper threshold temperature. Temperatures below or above the thresholds are not considered conducive for growth or development. Degree-day values are often used for modeling growth and development because they quantify "temperature" or "heat" unit accumulation on each day. The accumulation of heat units (e.g., degree-days) provides a measure of the developmental or growth rate.

Biological development rates are linearly related to temperature, but temperature has a diurnal trend. It is important to include this temperature variation in agricultural models such as those describing crop phenology and development on the basis of the accumulation of growing degree-days. Degree-days (°*D*) are determined by first calculating degree-hours (°*H*) for each hour of the day. The number of °*H* is calculated as the mean hourly temperature or the upper threshold, whichever is smaller, minus the lower threshold. To calculate °*D*, the °*H* are summed over the 24-h day and the sum is divided by 24 (Snyder 1985; Wilson and Barnett 1983).

Several studies have been directed toward improving the procedures for calculating the integral of the tempera-

Table 1 Location descriptions of selected California Irrigation Management Information System (CIMIS) weather stations

Station	Elevation (m)	Latitude	Longitude	Description
Calipatria	–33	33°02′N	115°24′W	A desert location below sea level. Very hot, dry and sometimes windy conditions in summer. Mostly clear to partly cloudy. Mild, partly cloudy winters with transitions in the spring and fall
Davis	18	38°35′N	121°46′W	A central valley location near Sacramento. Clear, hot, and dry with calm winds until late afternoon in summer. Moderate SW winds in late afternoon. Moderate and variable spring and fall conditions. Cool and foggy winter
Fresno	103	36°49′N	119°44′W	A dry central valley location, with nearly all precipitation between November and April. Sunny and hot summers. Winter with mild temperature, though minimum temperature occasionally drop below freezing. Dense, persistent and frequent fog during wintertime
Mac Arthur	1006	41°03′N	121°27’W	Northern mountain valley. Variable cloudy conditions much of the year. Warm dry summers and cool to cold winters with snow
Port Hueneme	5	34°10′N	119°12′W	A southern coastal location 60 miles northwest of Los Angeles. Mild temperature throughout the year with a typical ocean breeze regime

Table 2 Mean values of typical weather variables from the selected locations in California. The data are from California Irrigation Management Information System (CIMIS). P, annual average rainfall amount; T_x and T_n, mean annual maximum and minimum air temperature; RH_x and RH_n, mean annual maximum and minimum relative humidity; Wr, mean daily wind run

Station	Data collection period (years)	P (mm)	T_x (°C)	T_n (°C)	RH_x (%)	RH_n (%)	Wr (km day^{-1})
Calipatria	17	106	31.9	12.3	78	26	190
Davis	18	489	24.1	8.1	87	43	233
Fresno	12	316	24.2	9.2	88	44	174
Mac Arthur	17	472	18.8	1.0	91	43	171
Port Hueneme	7	465	20.0	11.0	87	59	172

ture curve, such as the triangle method and the sine-wave method and its modifications (Allen 1976; Baskerville and Emin 1969; De Gaetano and Knapp 1993; Roltsch et al. 1999; Yin et al. 1995). In addition, hourly temperature data are often not available. Using measured hourly data offers the most accurate °H and °D estimates, but maximum (T_x) and minimum (T_n) temperature data are often used to estimate °D by approximating diurnal temperature curves (Snyder et al. 1999; Zalom et al. 1983). Actual daily temperature curves are not symmetrical and their shape may vary considerably as a result of weather conditions at a given location and time of year.

A variety of methods with varying degrees of complexity have been developed to approximate diurnal temperature curves. These include linear models (Sanders 1975), simple curve-fitting models based upon sine curves or Fourier analysis (Acock et al. 1983; de Wit et al. 1978; Fernandez 1992; Floyd and Braddock 1984; Johnson and Fitzpatrick 1977; Kline et al. 1982; Parton and Logan 1981; Walter 1967; Wilkerson et al. 1983; Worner 1988), and models with a more complex energy budget (Goudriaan and Waggoner 1972; Lemon et al. 1971; Myrup 1969). It is useful to have accurate temperature trend models that are not site-specific. However, most empirical models show variable results (Reicosky et al. 1989; Wann et al. 1985).

The objectives of this paper are to (1) present an empirical model (TM) for diurnal temperature, (2) compare the accuracy of the TM model with three published models, and (3) compare °D values calculated using the four methods and single-triangle and single-sine-wave methods.

Materials and methods

Five automated weather stations from the California Irrigation Management Information System (CIMIS) provided the hourly air temperature data for this study. The station locations (Fig. 1) were selected to represent a range of California climates including coastal valleys, desert, and mountain regions (Table 1). They provide a wide range of climate conditions and hourly temperature trends (Table 2).

Temperature data for the years 1993–1995 at each site provided the parameters for the model. The 1996–1999 temperature data at each site were used for testing. All data were included irrespective of weather conditions during both the model calibration and tests.

In addition, the maximum (T_x) and minimum (T_n) daily temperature values coming from the same hourly mean temperature as used for the TM model comparison were employed to reconstruct a mean temperature daily cycle using three published models.

The first model (WAVE) was initially presented by de Wit et al. (1978) and was included in the subroutine WAVE in ROOTSIMU V. 4.0 by Hoogenboom and Huck (1986). The WAVE method uses a cosine function for the period from the time of minimum temperature to the time of maximum temperature and

Fig. 1 Location of selected CIMIS automated weather stations in California

another cosine function from the time of the maximum temperature to the time of minimum temperature the next day. The method fixes at 1400 hours the time of the maximum temperature, and at sunrise the time of the minimum temperature. No site-specific calibration is required.

In the Parton and Logan (1981) model (P&L), the daily course is described by a truncated sine function during day time and an exponential function at night. The model requires three parameters to determine (i) the time difference between the hour of maximum temperature and midday (α=1.80 h), (ii) the time difference between the hour of minimum temperature and sunrise (β=0.88 h), and (iii) the rate of temperature change from sunset to the hour of minimum temperature of the next day (γ=2.20). The parameters do not appear to be strongly site-specific (Reicosky et al. 1989).

The Wilkerson et al. (1983) model (WK), included in the SOYGRO model V5.3, divides the day into three segments: from midnight to 2 h after sunrise, daylight hours, and from sunset to midnight. Changes in temperature are assumed linear with time. Again, no site-specific calibration is required.

Using several statistics, the accuracy of the models was determined by comparing hourly measured data with estimated temperatures over a daily cycle for the period 1996–1999. A regression between estimated (T_e) and observed (T_o) hourly temperature data and the coefficient of determination (R^2) were calculated. As it is a measure of bias and variance from the 1:1 line, the root-mean-square error (RMSE) statistic was calculated to evaluate the overall accuracy of the predicted temperatures. The RMSE is calculated as

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(T_{\mathrm{e}i} - T_{\mathrm{o}i})^2}{n}} \tag{1}$$

where n is the number of hourly data.

The sum of the residuals (RES) and the sum of the absolute value of the residuals (ABSRES) were used to evaluate how consistent the models were in calculating air temperature throughout daily cycle. A value of RES close to zero indicates an unbiased model and smaller values of ABSRES indicate better performance. These statistics are useful to determine the tendency to overpredict or underpredict the temperature over a period of time. Mean daily RES and ABSRES values are given by

$$\mathrm{RES} = \frac{\sum_{i=1}^{n}(T_{\mathrm{o}i} - T_{\mathrm{e}i})}{d} \tag{2}$$

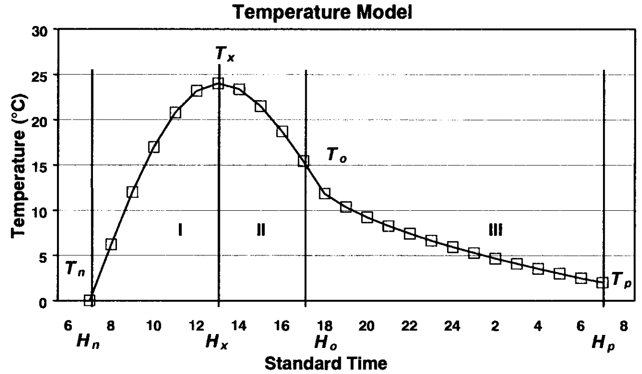

Fig. 2 Example of hourly temperature calculation by the TM model

and

$$\mathrm{ABSRES} = \frac{\sum_{i=1}^{n}\left|(T_{\mathrm{o}i} - T_{\mathrm{e}i})\right|}{d} \tag{3}$$

where d is the number of the days considered.

Hourly temperature data were also used to calculate growing degree-days (°D) using a lower temperature threshold of 10 °C. The °D values were calculated from estimated temperature data from the TM, P&L, WAVE, and WK models and were obtained by the single-triangle and single-sine wave methods (Baskerville and Emin 1969). These are well-known techniques that give good results when °D models are employed in the field (Roltsch et al. 1999). Single-triangle and sine-wave methods use T_x and T_n values to produce a triangle or sine curve and then calculate the °D value by determining the area above the threshold and below the curve (Pellizzaro et al. 1996; Zalom et al. 1983).

For each station, 4 years of average degree-day values accumulated monthly using each model (°$D_{\mathrm{ce}i}$) were compared with the observed monthly cumulative degree-day values (°$D_{\mathrm{co}i}$). The monthly percentage deviation from the standard (PD$_i$) was calculated as:

$$\mathrm{PD}_i(\%) = \frac{°D_{\mathrm{co}i} - °D_{\mathrm{ce}i}}{°D_{\mathrm{co}i}} \times 100 \tag{4}$$

where i indicates the month.

In addition, 4-year average PD$_i$ and standard deviation values were calculated for °D accumulated during the periods January through March, January through August, and January through December at each location.

For the same periods, the RMSE values were also calculated to evaluate the overall accuracy of the models in estimating the cumulative °D. RMSE is given by

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{j=1}^{m}\sum_{i=1}^{n}(°D_{\mathrm{ce}i} - °D_{\mathrm{co}i})}{n \times m}} \tag{5}$$

where n and m are the numbers of years and locations respectively.

Model development

The TM model divides the day into three segments (Fig. 2): from the sunrise hour (H_n) to the time of maximum temperature (H_x), from H_x to the sunset hour (H_o), and from H_o to the sunrise hour for the next day (H_p). The model uses two sine-wave functions in the daylight and a square-root decrease in temperature at night. H_n and H_o are determined as a function of the site latitude and the day of the year. H_p is calculated as H_p=H_n+24. The time of the maximum temperature is set 4 h before sunset (H_x=H_o–4).

Values for the temperature at H_n (T_n), H_x (T_x), and H_p (T_p) are input. T_n and T_x are the minimum and maximum temperature on the current day and T_p is the minimum on the following day. A value for the temperature at H_o (T_o) is calculated as

$$T_o = T_x - c\,(T_x - T_p) \tag{6}$$

where the c parameter is estimated empirically to be 0.39 by fitting the equation to the 1993–1995 hourly data set.

For given T_n, T_x, and T_p, as well as T_o from Eq. 6, the TM model calculates the hourly temperature $T(t)$ according to the following equations:

$$T(t) = \begin{cases} T_n + \alpha\left[\left(\dfrac{t - H_n}{H_x - H_n}\right)\dfrac{\pi}{2}\right] & H_n < t \le H_x \quad (7a) \\ T_o + R\sin\left[\dfrac{\pi}{2} + \left(\dfrac{t - H_x}{4}\right)\dfrac{\pi}{2}\right] & H_x < t < H_o \quad (7b) \\ T_o + b\sqrt{t - H_o} & H_o < t \le H_p \quad (7c) \end{cases}$$

In the above equations, t is the hour of the day in standard time, and α, R, and b are given by

$$\alpha = T_x - T_n \tag{8}$$

$$R = T_x - T_o \tag{9}$$

$$b = \frac{T_p - T_o}{\sqrt{H_p - H_o}} \tag{10}$$

Results and discussion

Model performance

An example of the 4-year mean daily temperature traces from TM and the three selected models (P&L, WAVE, and WK) along with the hourly measured temperatures for several months at Davis, Calif., is shown in Fig. 3. The general shapes of each curve reflect differences between the methods to be discussed in terms of model accuracy. The calculated curves for all but the P&L method gave a good estimate of the observed value during the period between midnight and the time of maximum temperature. The P&L model always overestimated the observed data. The TM model gave a substantially better fit to the observed data from the daily maximum to midnight. The magnitude of the errors for each method changed diurnally. The 4-year mean difference between the observed (T_o) and estimated (T_e) hourly temperature values for January, April, July, and October is shown in Fig. 4 for Davis, Calif. The smallest hourly errors resulted at the sunrise hour and after midday when all methods assume the input T_n and T_x. The absolute value of the error at other times of the day was always less than 3 °C for the TM and WAVE models, but it was as large as 6–9 °C for the WK and P&L models. Similar results were obtained from the other sites.

Table 3 shows the mean statistics obtained by comparing hourly temperature estimates from each of the four methods with observed hourly temperature data for all years and locations. In general, the TM model performed better than the others, with a slope (b) of the regression line close to 1.0 and an intercept (a) equal to 0.13. The lowest RMSE value was obtained for the TM model and the largest for the P&L model. The R^2 values ranged from a low of 0.91 for the P&L model to a high of 0.97 for the TM model. A large negative RES with the highest ABSRES value indicates a tendency for the P&L model to overpredict the observed temperature. The performances of the WAVE and WK models were similar in terms of RMSE and ABSRES, showing slight overestimation and underestimation respectively. The small RES

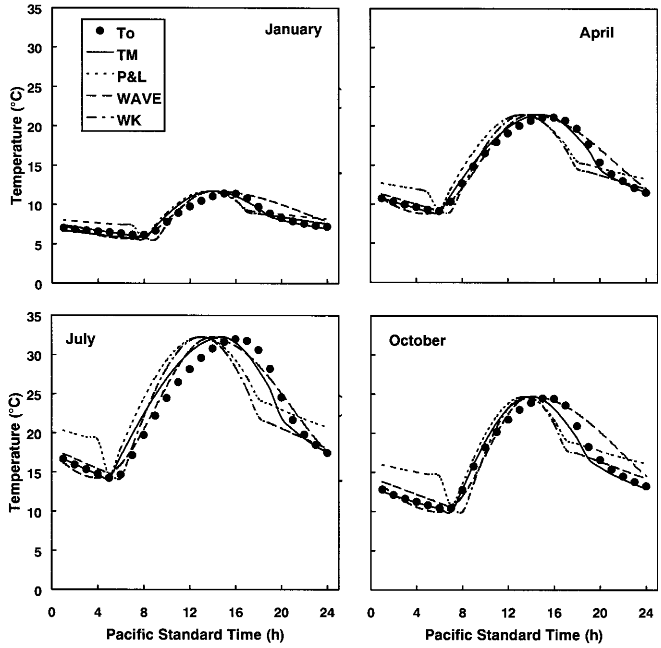

Fig. 3 Four-year (1996–1999) average observed and simulated hourly temperatures for January, April, July, and October at Davis, Calif. (*To* observed data, *TM* temperature model, *P&L* Parton and Logan model, *WAVE* de Wit model, *WK* Wilkerson model)

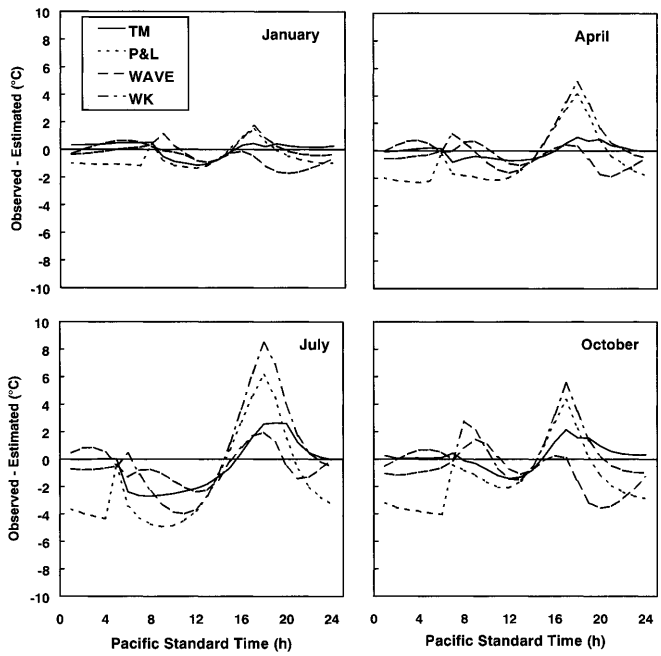

Fig. 4 Four-year (1996–1999) average hourly differences between the observed and estimated temperatures for January, April, July, and October at Davis, Calif. (*TM* temperature model, *P&L* Parton and Logan model, *WAVE* de Wit model, *WK* Wilkerson model)

Table 3 Overall regression statistics for the comparison between estimated and observed hourly temperature data for five locations in California during the period 1996–1999. The intercept (*a*) and the slope (*b*) of the regression line, the coefficient of determination (R^2), the sum of the residuals (RES), the sum of the absolute value of the residuals (ABSRES), and the root-mean-square error (RMSE) are reported (*TM* temperature model, *P&L* Parton and Logan model, *WAVE* de Wit model, *WK* Wilkerson model)

Model	*a*	*b*	R^2	RES	ABSRES	RMSE
TM	0.13	0.99	0.97	2.27	25.76	1.50
P&L	2.55	0.90	0.91	–22.12	52.37	2.93
WAVE	0.73	0.97	0.95	–7.32	33.36	2.03
WK	0.78	0.93	0.94	8.79	39.73	2.35

Table 4 Regression statistics for the comparison between estimated and observed hourly temperature data by model and season for five locations in California during the period 1996–1999

Model	Season	*a*	*b*	R^2	RES	ABSRES	RMSE
TM	Winter	0.27	0.96	0.95	1.78	25.48	1.53
	Spring	0.12	0.98	0.96	3.19	25.31	1.45
	Summer	0.47	0.98	0.96	0.69	26.70	1.52
	Autumn	0.18	0.98	0.97	3.43	25.79	1.50
P&L	Winter	2.56	0.83	0.83	–26.90	52.15	3.00
	Spring	2.51	0.87	0.87	–14.99	48.13	2.66
	Summer	2.75	0.90	0.89	–18.03	50.79	2.78
	Autumn	3.69	0.85	0.87	–28.87	58.76	3.24
WAVE	Winter	0.97	0.96	0.90	–14.48	36.90	2.28
	Spring	0.39	0.98	0.94	–2.28	30.73	1.87
	Summer	0.03	1.00	0.96	0.35	27.21	1.53
	Autumn	1.04	0.97	0.93	–13.10	38.78	2.34
WK	Winter	0.83	0.89	0.90	1.63	36.85	2.17
	Spring	0.77	0.91	0.90	12.68	38.47	2.30
	Summer	0.03	0.92	0.91	13.87	42.01	2.51
	Autumn	1.24	0.91	0.92	6.82	41.80	2.42

values show a tendency for the TM model to underestimate the observed temperature and the comparison of the ABSRES suggests that the error in the method tends to cancel-out over the daily period.

The models were also analyzed for accuracy by season and location. The error analysis for the data obtained from each model on the basis of the season is presented in Table 4. The results showed very little difference between the performance in different seasons for the TM model, which gave consistently the best accuracy. The P&L and WK models gave results comparable with those obtained from the overall analysis (Table 3). The WAVE model performance varied with the season, showing results better or comparable to the TM model in spring and summer.

Table 5 summarizes results of the error analysis by location. Again, the TM model performed as well or better than the three other models (WAVE), with RMSE values ranging from 1.44 (Port Hueneme) to 1.61 (Mac Arthur). The TM model showed a slight underestimate for all locations but Davis where a very small tendency to overpredict resulted. The P&L and WK models confirmed the tendency to overpredict and underestimate respectively. In all locations, they had RMSE values greater than 2 °C. The results from the WAVE model showed a general overestimate of the observed data, with a RMSE value varying from 1.58 (Davis) to 2.76 (Calipatria).

At Port Hueneme, all models showed the lowest R^2 values. A smaller R^2 indicates a bigger scatter about a regression line, but, if a model is accurate, the regression slope should be near unity and the intercept near zero. Only the TM model consistently had slopes near unity and intercepts near zero for all locations (Table 5). The reason for the larger scatter at Port Hueneme is attributed to fog, clouds, and variable winds at that coastal location, which alter the classic shape of the diurnal radiation and temperature curves. In general, the effect of the breeze coming from the ocean causes a decrease in incoming radiation and air temperature along with an increase of humidity from 9000 h to 1100 h, depending on the season, and results in a relatively small change in temperature during the day (Fig. 5).

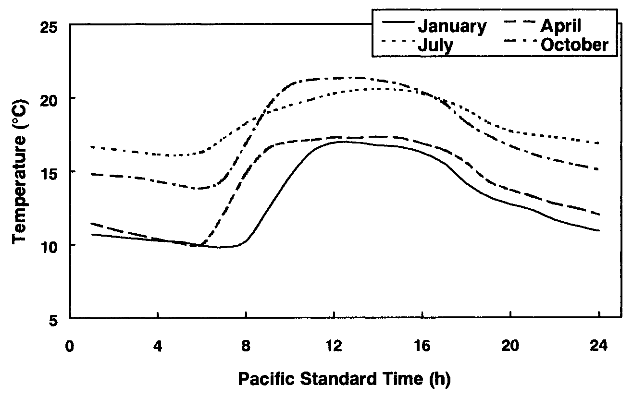

Fig. 5 Four-year (1996–1999) average observed hourly temperatures for January, April, July, and October at Port Hueneme, Calif.

Table 5 Regression statistics for the comparison between estimated and observed hourly temperature data by model and location during the period 1996–1999

Model	Location	*a*	*b*	R^2	RES	ABSRES	RMSE
TM	Davis	0.22	0.99	0.97	–1.95	25.62	1.47
	Fresno	0.17	0.98	0.97	4.72	26.80	1.49
	Calipatria	0.12	0.99	0.98	3.49	26.17	1.50
	Mac Arthur	0.08	0.99	0.97	0.14	27.85	1.61
	Port Hueneme	0.02	0.99	0.90	4.93	22.37	1.44
P&L	Davis	2.76	0.89	0.86	–25.37	57.52	3.09
	Fresno	2.60	0.89	0.92	–19.11	48.33	2.65
	Calipatria	4.10	0.86	0.91	–29.60	61.40	3.36
	Mac Arthur	2.01	0.89	0.90	–26.50	58.18	3.17
	Port Hueneme	3.63	0.79	0.71	–9.96	36.45	2.23
WAVE	Davis	0.55	0.99	0.96	–10.86	27.66	1.58
	Fresno	0.63	0.97	0.97	–4.39	28.65	1.68
	Calipatria	1.41	0.95	0.93	–10.00	47.30	2.76
	Mac Arthur	0.53	0.98	0.97	–9.38	31.82	1.89
	Port Hueneme	1.11	0.93	0.79	–1.95	31.37	2.03
WK	Davis	1.20	0.91	0.90	5.29	40.22	2.43
	Fresno	0.76	0.93	0.95	11.38	37.91	2.12
	Calipatria	1.22	0.92	0.93	12.10	49.80	2.80
	Mac Arthur	0.36	0.92	0.94	7.18	40.04	2.32
	Port Hueneme	0.43	0.89	0.79	7.99	30.67	2.01

Table 6 Four-year mean percentage deviation and standard deviation values between observed and estimated cumulative degree-days for each site during three periods (January–March, January–August, and January–December). Cumulative degree-day values were obtained using hourly temperatures from the estimation models (TM, P&L, WAVE, WK) and calculated by single-triangle (*ST*) and single-sine-wave (*SS*) techniques

Method	Site	Jan–Mar	Jan–Aug	Jan–Dec
TM	Calipatria	4.1±0.70	1.3±0.29	1.7±0.52
	Davis	0.4±2.54	–2.5±0.89	–1.8±0.84
	Fresno	2.4±1.90	2.3±0.97	2.3±0.74
	Mac Arthur	–7.0±6.42	–0.7±4.57	–1.1±4.30
	Port Hueneme	7.8±3.01	2.4±1.30	3.2±1.24
	Overall	4.0±1.04	0.8±0.62	1.2±0.46
ST	Calipatria	–5.8±1.48	–0.6±0.37	–1.6±0.51
	Davis	–7.0±3.94	–3.5±0.73	–4.7±0.68
	Fresno	–3.1±3.32	1.6±0.92	0.1±0.59
	Mac Arthur	6.9±8.63	3.1±4.92	1.1±4.39
	Port Hueneme	–1.3±3.62	0.1±1.72	–0.7±1.40
	Overall	–4.0±2.03	–0.1±0.66	–1.4±0.37
P&L	Calipatria	–14.0±2.61	–5.7±0.57	–7.1±0.59
	Davis	–14.9±5.27	–11.6±1.42	–12.4±1.21
	Fresno	–9.1±4.46	–3.6±1.00	–5.5±0.70
	Mac Arthur	–4.7±4.43	–7.6±5.28	–8.5±4.80
	Port Hueneme	–6.4±2.78	–3.8±1.50	–5.1±1.18
	Overall	–11.0±2.05	–6.2±0.56	–7.5±0.53
WAVE	Calipatria	–13.2±1.65	–1.8±0.49	–3.0±0.76
	Davis	–16.1±4.15	–4.8±1.17	–6.2±1.20
	Fresno	–11.7±2.67	0.3±0.93	–1.5±0.84
	Mac Arthur	–28.2±8.56	–1.7±4.49	–5.5±3.73
	Port Hueneme	–4.6±3.10	–1.0±1.26	–1.7±1.00
	Overall	–11.3±0.79	–1.7±0.59	–3.3±0.64
WK	Calipatria	11.5±2.80	5.5±0.54	5.2±0.51
	Davis	10.3±4.27	4.2±1.04	4.1±0.66
	Fresno	12.1±3.42	7.1±0.95	6.9±0.62
	Mac Arthur	14.4±6.96	9.3±4.64	9.5±4.59
	Port Hueneme	13.1±3.64	6.3±1.51	6.1±1.36
	Overall	11.9±2.52	6.1±0.80	5.9±0.51
SS	Calipatria	–20.2±7.76	–3.2±1.59	–4.5±1.32
	Davis	–27.9±7.75	–6.9±1.54	–8.9±2.04
	Fresno	–19.5±5.96	–1.0±1.31	–3.2±1.18
	Mac Arthur	–52.3±17.41	–5.5±6.92	–9.3±6.30
	Port Hueneme	–7.0±6.29	–1.7±2.82	–2.6±2.70
	Overall	–18.3±7.48	–3.4±1.61	–5.2±1.51

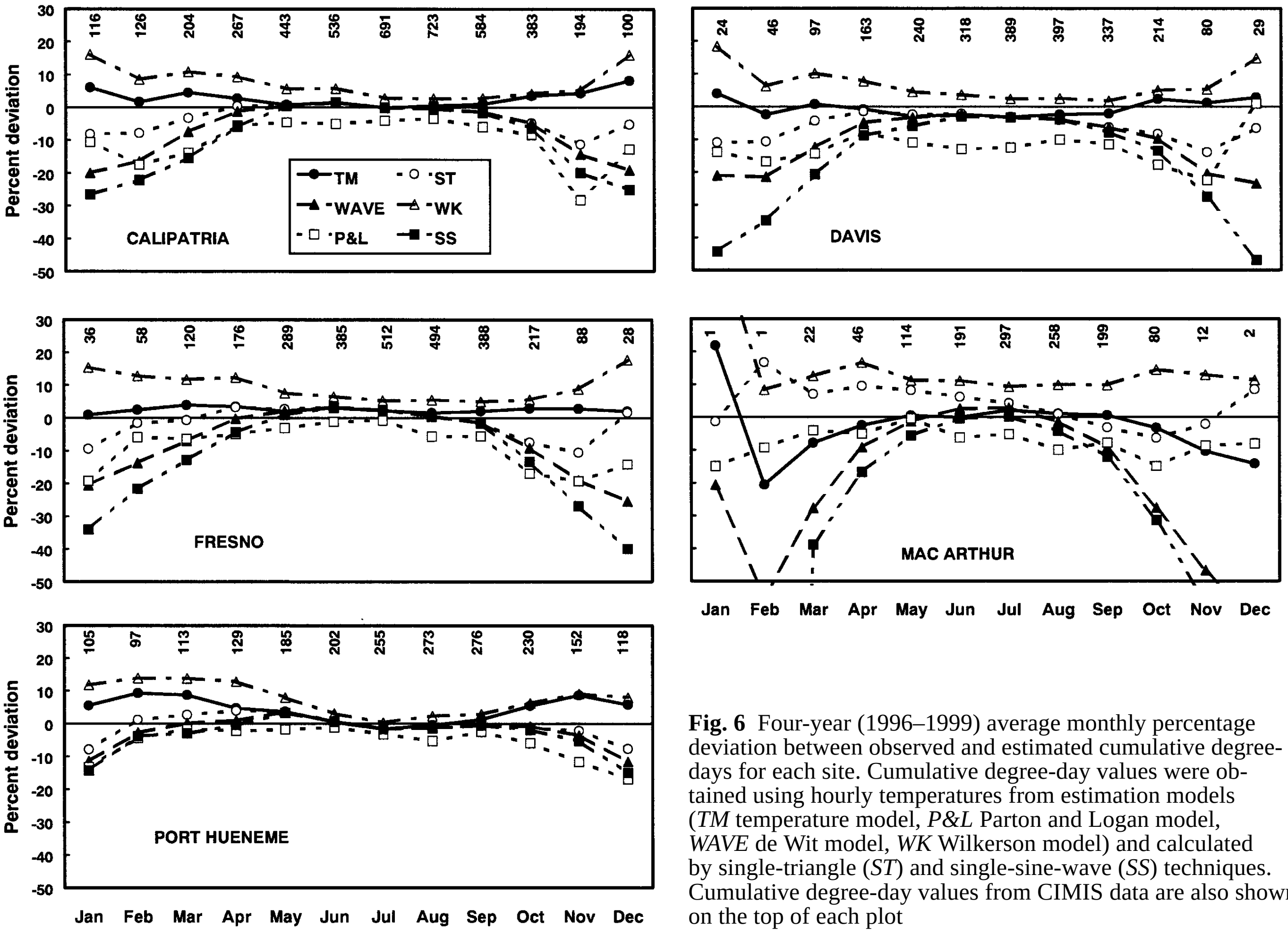

Fig. 6 Four-year (1996–1999) average monthly percentage deviation between observed and estimated cumulative degree-days for each site. Cumulative degree-day values were obtained using hourly temperatures from estimation models (*TM* temperature model, *P&L* Parton and Logan model, *WAVE* de Wit model, *WK* Wilkerson model) and calculated by single-triangle (*ST*) and single-sine-wave (*SS*) techniques. Cumulative degree-day values from CIMIS data are also shown on the top of each plot

The TM model R^2 was smallest for Port Hueneme, but the RMSE was also the smallest for any model and location combination. Therefore, Port Hueneme had the smallest absolute error, which is partly due to a smaller temperature range at the coastal location. The other models were less accurate than the TM model, with variable slopes and intercepts that were not consistently close to unity and zero respectively.

Growing degree-day estimate

The TM model was also analyzed for accuracy when hourly temperature data were used to calculate °*D*. A comparison between °*D* calculated from the TM model, the other selected models, and the commonest methods (single-triangle and single-sine-wave) used to estimate °*D* is presented.

For each site, the 4-year average monthly percentage deviation from the standard (PD_i) is plotted for the different methods (Fig. 6). The comparison indicates that the performance of the TM and single-triangle methods was superior to that of the other models with very small absolute deviations (always below 5%) from May to September at all sites and an absolute error up to 10% during autumn and winter months. All methods showed erratic results at Mac Arthur, although the TM model again gave the best performance. In general, differences resulting in a considerable increase in errors occurred for all methods and locations during winter months when the estimated cumulative degree-day values were small. This is most likely because the observed winter temperatures were frequently near or below the threshold (10 °C).

The 4-year percentage deviation mean values along with the standard deviations by each location are presented in Table 6 for three periods (from January through March, from January through August, and from January through December).

Again, the TM and single-triangle models performed better than the other methods. The TM model tended to underestimate and the single-triangle model overestimate °*D* values slightly for most sites. The other methods were less accurate at all locations with the P&L, WAVE, and single-sine-wave models giving an overestimate and the WK model underestimating. Comparatively, the single-sine-wave method produced the most error, having the biggest deviations for almost all locations and periods. Generally, larger percentage deviations were obtained for the period from January through March.

To test the accuracy of the models in calculating cumulative °*D*, the overall (all sites and years) RMSE values were determined from January through March,

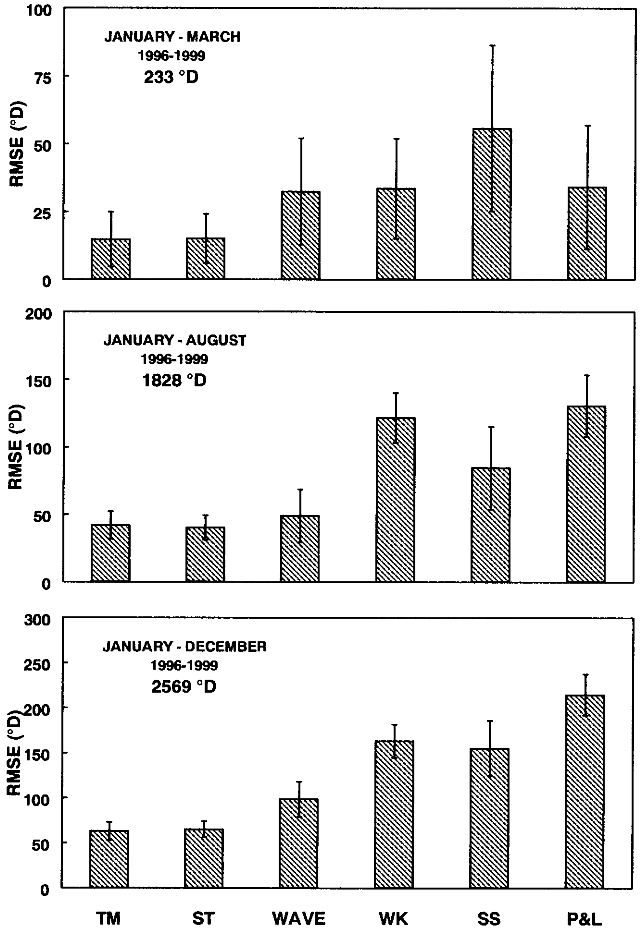

Fig. 7 Four-year (1996–1999) overall (all sites) root-mean-square error (RMSE) of cumulated degree-days (°*D*) for three different periods of the year (January–March, January–August, and January–December). Cumulative degree-day values were obtained using hourly temperatures from estimation models (*TM* temperature model, *P&L* Parton and Logan model, *WAVE* de Wit model, *WK* Wilkerson model) and calculated from single-triangle and single-sine-wave techniques. The standard deviation of the RMSE by site is also shown

from January through August, and from January through December for each method. In addition, the variability of the RMSE by site was evaluated by calculating the standard deviation. As shown in Fig. 7, the smallest errors were obtained for the TM and single-triangle methods with values of RMSE ranging from 2% (January–August, January–December) to 6% (January–March) of the observed cumulative °*D*. A similar variation of the RMSE throughout the year was obtained from the other models but with a larger range of values. The poorest accuracy was obtained for the P&L, WK and single-sine-wave models with RMSE values two to four times larger than those obtained for the TM and single-triangle models. The WAVE model gave reasonable results; however, the site variation was larger than for the TM and single-triangle models. Although the accuracies of the TM and single-triangle models were similar, the site variability of the RMSE values was smaller for the TM model.

Conclusions

A diurnal temperature trend model (TM) has been presented and compared with published models from the literature, using hourly temperature data from an automated weather network. The TM and WAVE (de Wit et al. 1978) models generally provided more accurate estimates of temperature trend than did the P&L (Parton and Logan 1981) and WK (Wilkerson et al. 1983) models using hourly weather data for 4 years from five locations with very different climate. On a seasonal basis, the TM model was superior to the WAVE model, which was considerably more accurate than the others. Also the analysis by location showed that the TM model performed better than the other models, although the WAVE method gave reasonable accuracy. All models showed a larger scatter at Port Hueneme, which is located in a foggy coastal area. Since each model is developed to reconstruct an approximately sinusoidal path of temperature that is typical of sunny days, factors other than radiation can assume more importance in determining the air temperature curve in a foggy coastal area. In any case, the best overall prediction (i.e., the lowest RMSE values) was obtained at Port Hueneme. However, the small RMSE values are partly due to a smaller temperature range at the coastal Port Hueneme location.

When the temperature trend data were used to calculate cumulative growing degree-day values, the TM model again was the best in general, regardless of the season of degree-day accumulation. Larger percentage errors of the estimate were obtained for all models during winter and at the mountain site (Mac Arthur), when cumulative degree-day values were small. The single-triangle model also gave good results; however, it seemed more affected by site variability.

The results suggested that the TM model is a simple and accurate method to approximate the daily temperature curve from maximum and minimum daily temperatures and calculate growing degree-day values.

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