

ACCURACY OF HOURLY AIR TEMPERATURES CALCULATED FROM DAILY MINIMA AND MAXIMA*

D.C. REICOSKY, L.J. WINKELMAN, J.M. BAKER, and D.G. BAKER**

North Central Soil Conservation Research Laboratory, Agricultural Research Service, USDA, Morris, MN 56267 (U.S.A.)

(Received April 25, 1988; revision accepted September 30, 1988)

ABSTRACT

Reicosky, D.C., Winkelman, L.J., Baker, J.M. and Baker, D.G., 1989. Accuracy of hourly air temperatures calculated from daily minima and maxima. *Agric. For. Meteorol.*, 46: 193-209.

Temperature is one of the critical variables that drives biological systems and is of fundamental importance in crop growth models. The objective of this work was to determine the accuracy of several methods for calculating hourly air temperatures from daily maxima and minima. Methods that have as inputs daily minimum and maximum temperature were selected from the literature based on their use in existing growth models and simplicity. Four years of hourly air temperature data collected during the growing season at 2 m over well-watered grass were used to test the various methods. Six days from each growing season were randomly selected for detailed analysis, and an additional 9 days were selected to cover a range of daily maximum temperatures and solar radiation. The absolute mean error within a 24-h period ranged from 0.5 to 9.3°C for the 6 randomly selected days for all 4 years of the data. All methods worked reasonably well on clear days but with limited success on overcast days. Daily maximum temperature did not appear to affect the accuracy of any of the methods. If accurate timing of temperature input to models is critical, the results indicate direct measurement of hourly temperature may be necessary.

INTRODUCTION

Temperature is one of the critical variables that drives all biological systems. Air temperature is a fundamental input requirement for many agricultural models, particularly crop growth models. For the validation of agricultural models and for climatological purposes, many of the available data consist of only the daily minimum and maximum temperatures. For many models it is often useful to obtain an approximation of hourly temperature for a particular location and time of the year.

*In cooperation with the Minnesota Agricultural Experiment Station, Sci. J. Series No. 15, 966.

**Soil Scientist, USDA-ARS, Morris, MN, Sr. Systems Analyst, University of Minnesota, Morris, MN, Soil Scientist USDA-ARS, St. Paul, MN, and Professor of Soil Science, University of Minnesota, St. Paul, MN.

The shape of the diurnal temperature curves has been modeled in a variety of ways that vary from simple curve-fitting models based upon sine curves (Allen, 1976; Hansen and Driscoll, 1977; Johnson and Fitzpatrick, 1977a, b; Room and Kerr, 1983; Floyd and Braddock, 1984; Wann et al., 1985; Kimball and Bellamy, 1986) to more sophisticated techniques utilizing Fourier analysis (Carson, 1963) and complex energy balance models (Carson and Moses, 1963; Brown, 1969). Since many of the observed diurnal temperature curves are a combination of periodic sine and exponential decay curves, they are not easily represented by a few terms in a Fourier series.

Several soyabean plant growth models have been developed and have shown reasonable results for a limited number of data sets (SOYGRO, Wilkerson et al., 1983; GLYCIM, Acock et al., 1983; and SOYMOD, Curry et al., 1975). The applicability of these models in other parts of the soyabean production areas needs to be tested. One of the first steps in testing any crop growth model is to determine the accuracy of the temperature routines that utilize daily minimum and maximum as inputs. Thus, the objective of this study was to determine the accuracy of several methods for calculating hourly temperatures during the growing season from daily minima and maxima. Methods were selected that were presumed to be not site specific and that required limited inputs for calculating hourly temperatures from daily minimum and maximum. The results were compared with hourly data collected in west central Minnesota.

METHODS AND MATERIALS

Methods of calculating hourly temperature

Three different methods of calculating temperature were selected because of their use in existing soyabean growth models, and two additional methods were selected because of their simplicity. All models have as inputs at least the daily minimum and maximum air temperature, and some require location latitude and longitude to calculate sunrise and sunset times from standard meteorological equations (List, 1966). The general diurnal pattern of each method with the same maximum (*TMAX*) and minimum (*TMIN*) input is illustrated in Fig. 1, along with the hourly temperatures from the same representative data set. *TMAX* and *TMIN* establish the temperature limits of each method and control only the vertical spread in the hourly values. The general shapes reflect differences in each of the methods to be discussed in further detail.

Method 1

Method 1 was initially presented by De Wit et al. (1978) and was obtained from the subroutine WAVE in ROOTSIMU V4.0 by Hoogenboom and Huck (1986). This method requires *TMIN* of the next day and divides the day into

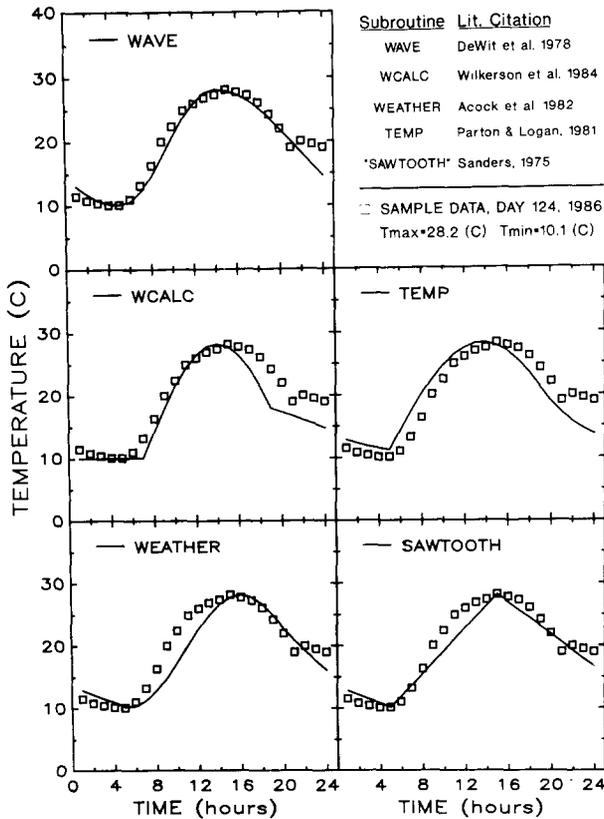


Fig. 1. The general shape of the curves for the five methods of calculating hourly temperature compared with a representative data set of observed temperatures.

two segments, from sunrise to 1400 h and from 1400 h to sunrise of the next day. The method assumes T_{MAX} at 1400 h and T_{MIN} at sunrise, and the intervening temperatures are calculated from the following equations

for $0 \leq H < RISE$ and $1400 \text{ h} < H \leq 2400 \text{ h}$

$$T(H) = TAVE + AMP \cos(\pi H' / (10.0 + RISE))$$

for $RISE \leq H \leq 1400 \text{ h}$

$$T(H) = TAVE - AMP \cos(\pi(H - RISE) / (14 - RISE))$$

where $RISE$ is the time of sunrise in hours and $T(H)$ is the temperature at any hour, H is time in hours, $H' = H + 10$ if $H < RISE$, $H' = 14$ if $H > 1400$ h and $TAVE$ and AMP are defined as $TAVE = (T_{MIN} + T_{MAX})/2$ and $AMP = (T_{MAX} - T_{MIN})/2$, respectively.

Method 2

Method 2 was adopted from the Model SOYGRO V5.3 described by Wilkerson et al. (1983) from the subroutine WCALC. The day is divided into 3 segments: (a) midnight to sunrise + 2 h; (b) daylight hours; (c) sunset to

midnight. The method assumes a change from night to day temperature at sunrise + 2 h, and the night temperatures are linear with time. In addition to the current day's *TMAX* and *TMIN*, the method requires the *TMAX* and *TMIN* of the previous day and the *TMIN* of the following day. The hourly temperatures are given by

(a) midnight to sunrise + 2 h

$$\begin{aligned} TAU &= \pi(SET_{n-1} - RISE_{n-1} - 2) / (SET_{n-1} - RISE_{n-1}) \\ TLIN &= TMIN_{n-1} + (TMAX_{n-1} - TMIN_{n-1}) \sin(TAU) \\ SLOPE &= (TLIN - TMIN_n) / (24 - SET_{n-1} + RISE_n + 2) \\ T(H) &= TLIN - SLOPE(H + 24 - SET_{n-1}) \end{aligned}$$

(b) sunset to midnight

$$\begin{aligned} TAU &= \pi(SET_n - RISE_n - 2) / (SET_n - RISE_n) \\ TLIN &= TMIN_n + (TMAX_n - TMIN_n) \sin(TAU) \\ SLOPE &= (TLIN - TMIN_{n+1}) / (24 - SET_n + RISE_{n+1} + 2) \\ T(H) &= TLIN - SLOPE(H - SET_n) \end{aligned}$$

(c) daylight hours

$$\begin{aligned} TAU &= \pi(H - RISE_n - 2) / (SET_n - RISE_n) \\ T(H) &= TMIN_n + (TMAX_n - TMIN_n) \sin(TAU) \end{aligned}$$

where

TAU, *TLIN*, *SLOPE* are temporary variables in calculations

T(H) = temperature at hour *H*

n = current day of the year (1-365)

RISE = time of sunrise (h)

SET = time of sunset (h).

Method 3

Method 3 was adopted from the model GLYCIM described by Acock et al. (1983) using the subroutine WEATHER to generate hourly temperatures. The day is divided into 3 segments similar to Method 2 and also requires the previous day's *TMAX* and *TMIN* and the following day's *TMIN*, as well as the daily solar radiation. *TMIN* is assumed to occur at sunrise, and the night temperature decreases exponentially to *TMIN* of the next day. The time of *TMAX* is assumed to be an empirical function of the instantaneous solar radiation at noon. The function was developed at Mississippi and checked in Arizona (B. Acock, personal communication, 1987). The instantaneous solar radiation is calculated from the integrated daily radiation using the day length and *TMAX*, assuming the radiation flux density varies as a half sine wave over the daylight period. The empirical relationship between the time of *TMAX* and instantaneous radiation developed for Mississippi and used here is given by

$$\begin{aligned} TMAXHR &= DAYLNG / \pi(\pi - \arcsin(X)) \\ X &= TMAX / (0.0945 - (WATACT \ 8.06E-5) + (TMAX \ 6.77E-4)) / \\ &WATACT \text{ if } X > 1 \text{ then } X = 1 \end{aligned}$$

where

$TMAXHR$ = time between $TMAX$ and $DAWN$ (h)

X = intermediate variable, ≤ 1

$DAYLNG$ = length of day (h)

$TMAX$ = maximum air temperature ($^{\circ}C$)

$WATACT$ = actual radiation incident at earth's surface at noon calculated from daily radiation integral ($W\ m^{-2}$).

Having obtained the time of $TMAX$, the hourly temperatures are calculated from the following equations

(a) before dawn

$$T(H) = TDUSK_{n-1} \exp(\ln(TMIN / TDUSK_{n-1}) / (2DAWN) (DAWN + H))$$

(b) daytime

$$T(H) = (((TMAX - TMIN) / 2) (1 + \sin(((\pi / TMAXHR) (H - DAWN)) + 1.5\pi))) + TMIN$$

(c) after dusk

$$T(H) = TDUSK_n \exp(\ln(TMIN_{n+1} / TDUSK_n) / (2DAWN) (H - DUSK))$$

where

$T(H)$ = temperature at hour H

$$TDUSK = (((TMAX - TMIN) / 2) (1 + \sin(((\pi / TMAXHR) DAYLING + 1.5\pi)))) + TMIN$$

n = day of year

$DAWN$ = time of dawn (1/2 day length before noon)

$$= 12 - (DAYLNG / 2)$$

$DUSK$ = time of dusk (1/2 day length after noon)

$$= 12 + (DAYLNG / 2).$$

Since solar radiation is required in most crop growth models, it was not deemed too cumbersome to include it as an additional input. As will be shown later, the empirical relationship may not be applicable for northern climates, as indicated by the magnitude of the errors when compared to the other methods. Further testing is needed to determine the validity of this relationship for other locations.

Method 4

Method 4 was developed by Parton and Logan (1981). It will be referred to as the TEMP subroutine that divides the day into two segments and utilizes a truncated sine wave in the daylight and an exponential decrease in temperature at night. The day and night lengths are calculated as a function of DY (day of year) and latitude. It assumes $TMAX$ occurs in the daylight hours before sunset and that $TMIN$ occurs within a few hours of sunrise. The hourly temperatures are given by the following equations

(a) for daylight hours

$$T(H) = (TMAX - TMIN) \sin\left(\frac{\pi m}{y + 2a}\right) + TMIN$$

(b) for night-time hours

$$T(H) = TMIN + (TSUNSET - TMIN) \exp\left(-\frac{bn}{z}\right)$$

where $T(H)$ is the temperature at any hour of the day or night period determined from m and n

y = day length (h)

z = night length (h)

$TSUNSET$ = temperature at sunset ($^{\circ}\text{C}$)

m = number of hours between time of $TMIN$ and sunset (h)

n = number of hours from sunset to the time of $TMIN$ (h)

a = lag coefficient for $TMAX$ = 1.80 (h)

b = night-time temperature coefficient = 2.20

c = lag time of $TMIN$ from time of sunrise = 0.88 (h).

The coefficients a , b and c may vary slightly as a function of height and location and were found by parameter optimization for the 1.5-m height (Parton and Logan, 1981). Based on our preliminary results, these parameters did not appear to be strongly site specific and were assumed for our location. However, Wann et al. (1985) found different coefficients for North Carolina when compared with those for Colorado.

Method 5

Method 5 was a modification of that described by Sanders (1975), which assumes temperature to be a linear function of time between the $TMAX$ and $TMIN$ of consecutive days that results in a modified "SAWTOOTH" pattern. Additional inputs are the $TMAX$ for the previous day and $TMIN$ of the following day. The method assumes that $TMIN$ occurs at 0500 h and $TMAX$ at 1500 h. Some adjustment can be made for the rise and fall time during the daylight hours to more accurately reflect the diurnal trends (Sanders, 1975).

Data collection

The air temperature data used to check the accuracy of the various methods of calculating hourly temperatures were collected at the University of Minnesota West Central Experiment Station (latitude $45^{\circ}35'$ N, longitude $95^{\circ}55'$ W, elevation 344 m). The data were collected using a shielded thermocouple aspirated at 2 m over well-watered grass in a weather station from approximately 1 week before planting to 1 week after harvest during the 1983–1986 growing seasons that generally ranged from early May through mid-September. The temperatures were logged on the hour (Central Daylight Time), using a computer-controlled data acquisition system, temporarily stored, and then transmitted daily to a larger computer for further processing. The overall data acquisition system accuracy for the temperature measurements was 0.2°C . The data were collected as part of a more comprehensive climate data set.

To evaluate the accuracy of the calculation methods in fitting the diurnal temperature fluctuations within a 24-h period, 6 days from each growing season were randomly selected for detailed evaluation using a random number generator. Nine additional days were selected to cover a range of daily maximum temperature and solar radiation where daily maximum temperature was within the range of 10–20, 20–30 and 30–40°C, corresponding to cool, intermediate and warm, respectively. The daily irradiance ranged from <15, 15–25, and >25 MJ, corresponding to cloudy, partly cloudy and clear, respectively.

Methods of error analysis

To test the accuracy of the various models, temperatures measured at hourly intervals were compared to the calculated values over a 24-h interval. The “goodness of fit” of each of the models was assessed in several ways. First, the absolute mean error (AME), defined as the sum of the absolute value of the difference between the estimated and observed temperature for a 24-h period, is given by

$$\text{AME} = \sum_{i=1}^n |(Te_i - To_i)| / n$$

where n is the number of observations, Te is the estimated temperature and To is the observed temperature at any time. The AME has intuitive appeal and is useful for evaluating the model to predict the rate of development of an organism using a degree-hour summation.

The root mean square error (RMSE) calculated to reflect the overall accuracy of the shape of the predicted curve is defined by

$$\text{RMSE} = \left[\sum_{i=1}^n (To_i - Te_i)^2 / n \right]^{1/2}$$

The closer the estimated temperatures are to the observed temperature, the smaller the RMSE. The RMSE tends to penalize large individual errors heavily and as such may be the better criterion of performance.

The sum of the residuals and the sum of the absolute value of the residuals following Heuer et al. (1978) can be used to determine the tendency for the model consistently to overpredict or underpredict the temperature over a period of time. The sum of the residuals is given by the following equation

$$\text{RES} = \sum_{i=1}^n (To_i - Te_i)$$

where n is the number of hours being considered. The sum of the absolute residuals is expressed as

$$|\text{RES}| = \sum_{i=1}^n |(T_{o_i} - T_{e_i})|$$

By comparing RES to $|\text{RES}|$, one can determine how errors in the model will cancel over a period of time. A large positive RES that approaches $|\text{RES}|$ suggests that the model consistently underestimates the actual value. A large negative RES compared to $|\text{RES}|$ indicates a tendency for the model to overpredict the actual value. A small value for RES in comparison to $|\text{RES}|$ suggests that the errors in the model tend to cancel over the 24-h period.

RESULTS AND DISCUSSION

Performance on randomly-selected days

The data for the random days were grouped and analyzed using the 4-year means of the various error parameters to draw conclusions about the accuracy of each method with selected examples of the daily results to show the magnitude of error that is possible within a single day.

An example where all of the methods for calculating hourly temperatures worked reasonably well is illustrated in Fig. 2. This date (DY 176, 1986) was selected because the diurnal trend was smooth throughout the 24-h period, the range between maximum and minimum was large (18.3°C), and most of the assumptions of the models were met. The calculated results for all methods are reasonably close to the observed values; however, there are subtle differences

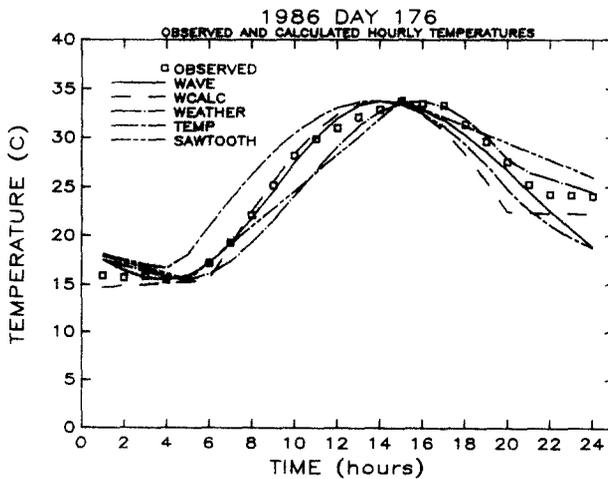


Fig. 2. Summary of the trend of the differences between the estimated and the observed temperatures for each of the methods on Day 176, 1986.

between the observed and estimated temperatures for each of the methods. For example, TEMP calculated a higher temperature earlier in the daylight hours, whereas SAWTOOTH was consistently lower after Hour 18. The magnitude of the errors with each of the methods seems to change through the 24-h period and is more easily noted by plotting the hourly error, i.e. the difference between the observed temperatures (T_o) and the estimated temperatures (T_e) in Fig. 3 for the same day. As would be expected, the difference between T_e and T_o is smallest at about Hour 5 and at Hour 14 when most of the methods assume the input T_{MIN} and T_{MAX} , respectively. Errors at other times of the day are as large as 5°C , with the time of maximum error varying among the different methods.

The error analysis for DY 176, 1986 shown in Figs. 2 and 3 is summarized in Table 1. The RMSE varied from a low of 1.5 for WAVE to 2.8 for TEMP. The

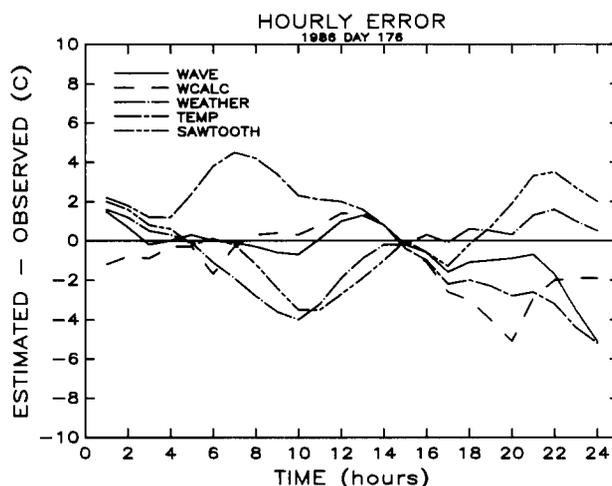


Fig. 3. Hourly temperatures calculated by the five methods vs. time compared with observed data for a randomly-selected Day 176, 1986, representing one of the randomly-selected days where the fit for most methods was generally good and the difference between T_{max} and T_{min} was 18.3°C .

TABLE 1

Summary of the statistics for Day 176, 1986, illustrating the magnitude of the errors on a day when all methods fit the observed data reasonably well

STAT.	WAVE	WCALC	WEATHER	TEMP	SAWTOOTH
R^2	0.95	0.94	0.94	0.82	0.91
AME	1.0	1.5	1.2	2.5	1.6
RMSE	1.5	1.9	1.7	2.8	2.0
RES	-12.6	-24.9	-10.6	7.3	0.6
RES	24.0	35.6	29.6	59.5	37.9

AME varied from a low of 1.0 to 2.5 for the same methods. In this case the correlation coefficient R^2 varied from a low of 0.82 for TEMP to a high of 0.95 for WAVE, suggesting reasonable fit, based on the overall diurnal trend. The RES and the $|\text{RES}|$ show relatively small numbers with the exception of TEMP that had $|\text{RES}|$ of 59.5. Table 1 indicates that most of the methods showed approximately the same magnitude of error, depending on the error parameter. The simplistic assumptions in SAWTOOTH result in errors that are essentially of the same magnitude as the more sophisticated sine and cosine methods.

A second example of the daily results is summarized in Fig. 4. This day's data (DY 199, 1985) were selected to illustrate a relatively poor fit of all of the methods for calculating hourly temperatures. There was not a smooth trend in the observed temperatures and only a small difference between the T_{MAX} (25.9°C) and the T_{MIN} (20.4°C). This small range of temperatures resulted in relatively small errors on an absolute basis. The trends throughout the 24-h period were not well fitted because the diurnal trends of the observed temperature were not smooth and did not closely match the assumptions in the various methods. The largest difference between T_e and T_o was -3.3°C for SAWTOOTH shown in Fig. 5. All other methods had maximum errors that were slightly lower that occurred around midday. As in the previous day's data, the minimum errors are associated with the time of T_{MIN} and T_{MAX} . The trend in the difference between T_e and T_o was similar for all the methods, with only the magnitudes of the errors being slightly different.

The error parameters for DY 199, 1985, are summarized in Table 2. As would be expected, the R^2 values for all the methods are relatively low compared to

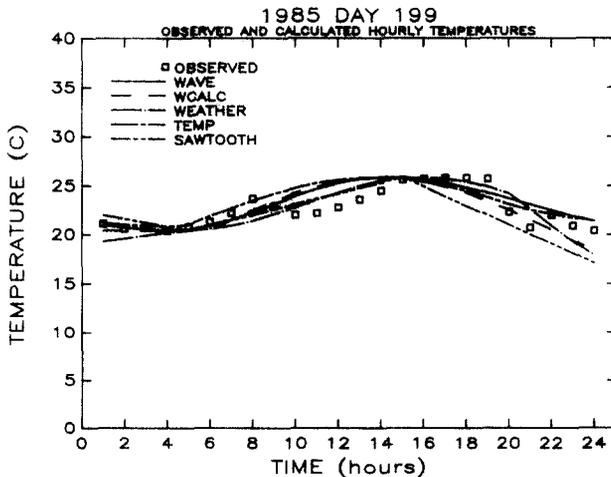


Fig. 4. Summary of hourly temperatures calculated by the five methods on Day 199, 1985, vs. time representing one of the randomly-selected days where the fit for most methods was not very good and the difference between T_{max} and T_{min} was 5.5°C .

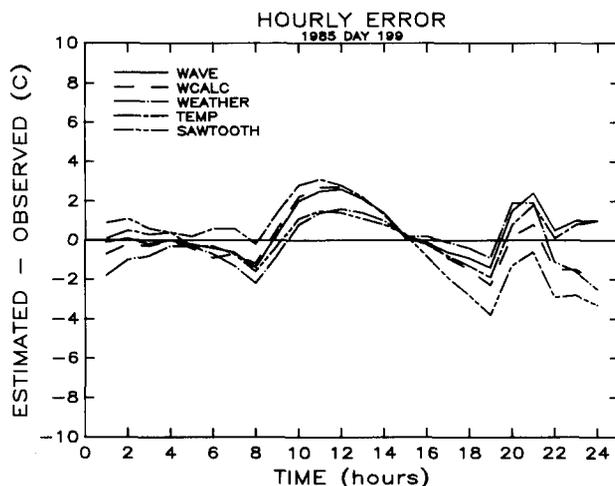


Fig. 5. Summary of the time trend of the difference between the estimated and the observed temperature for each of the methods on Day 199, 1985.

TABLE 2

Summary of the statistics for Day 199, 1985, illustrating the magnitude of the errors on a day when none of the methods fit the data very well

STAT.	WAVE	WCALC	WEATHER	TEMP	SAWTOOTH
R^2	0.65	0.63	0.75	0.62	0.50
AME	1.0	1.1	1.1	1.1	1.4
RMSE	1.3	1.4	1.3	1.4	1.7
RES	11.7	- 1.4	- 5.5	16.6	-14.3
RES	23.5	27.1	26.0	25.4	32.7

the previous day, with the R^2 ranging from the low of 0.5 for SAWTOOTH to a high of 0.75 for WEATHER. The AME ranged from 1.0 to 1.4, showing all the methods reasonably close. A similar trend is shown in the RMSE. On this day even though the R^2 values were lower than those for DY 176, 1986, the RES and |RES| were smaller, due to the smaller spread between the maximum and minimum temperature (5.5 vs. 18.3°C). The variation among the methods in the different error parameters was not consistent, and no one method was the best in all of the error parameters.

In order to look at the diurnal trends of the errors for the individual methods, the RMSE was plotted as a function of time for the 6 random days in each year. The trends within a year were essentially the same for all 4 years, with the minimum error at the time of the T_{MIN} and T_{MAX} . However, each of the methods had different times when the maximum RMSE occurred. As a result

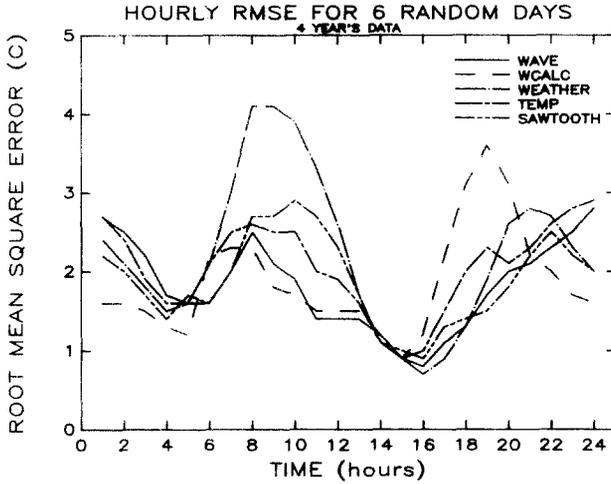


Fig. 6. The 4-year average of the root mean square error (RMSE) as a function of time during the day for the 6 randomly-selected days.

of the similarity across the 4 years, the RMSE for the 24 days representing the 6 random days from each of the 4 years is presented in Fig. 6. Of particular interest is the maximum RMSE for the various methods at various times during the day. The maximum RMSE was 4.1°C for WEATHER at Hour 8. The maximum for WCALC was 3.6°C at Hour 19. The maximum for TEMP was 2.9°C at Hour 24. In most cases both WAVE and WCALC show an RMSE of less than 2.5°C during the daylight hours. The importance of these errors as a function of time is related to the physiological processes that are being modeled. For example, if transpiration or photosynthesis is being modeled, then it would be necessary to have the most accurate calculations during the daylight hours, presumably during midday when these processes would be at the maximum. However, if respiration or frost hardiness is being modeled, it is important to calculate the temperatures accurately at night.

Performance on selected types of days

Analysis of the days selected on the basis of temperature regime (Fig. 7) showed that all models had a somewhat lower accuracy (R^2) at low temperatures, but there was little difference between the performance on warm and hot days. The effect of solar radiation (Fig. 8) is more obvious. The accuracy of all the models tested improves in inverse proportion to cloud cover. This is not unexpected, since the models are all constructed to mimic the classic diurnal swing of temperature that is most clearly expressed on sunny days where global irradiance at the surface follows a sinusoidal path. On cloudy days, fac-

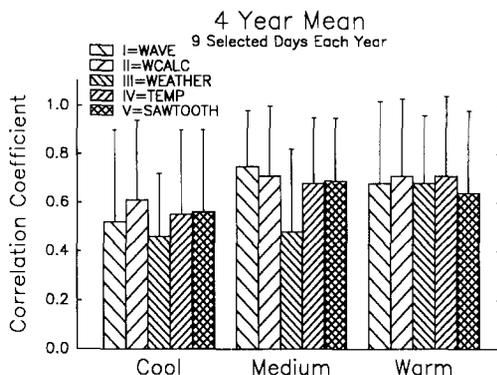


Fig. 7. Summary of the 4-year mean of the R^2 for each of the five methods for cool, medium and warm days.

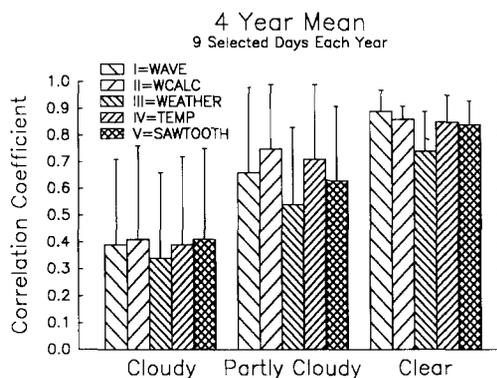


Fig. 8. Summary of the 4-year mean of the R^2 for the five methods for cloudy, partly cloudy and clear days.

tors other than radiation assume more importance in determining air temperature, altering the shape of the diurnal temperature curve.

OVERALL COMPARISON

The 4-year mean statistics for the 6 random days only are summarized in Table 3 for each of the five methods. The R^2 values ranged from a low of 0.70 for WEATHER to a high of 0.80 for WCALC. The AME and the RMSE showed similar trends, only slightly different in magnitude. By comparing RES to $|\text{RES}|$, one can determine how well the errors in the model will cancel over a period of time for integrated degree-hour calculations. A large positive RES that approaches $|\text{RES}|$ suggests that the model consistently underestimates the observed temperature. A large negative RES in comparison with $|\text{RES}|$

TABLE 3

Summary of the 4-year mean statistics for the randomly-selected days only

STAT.	WAVE	WCALC	WEATHER	TEMP	SAWTOOTH
R^2	0.79	0.80	0.70	0.75	0.77
AME	1.37	1.54	1.79	1.67	1.55
RMSE	1.82	1.94	2.32	2.08	1.90
RES	- 7.28	- 14.70	- 8.77	2.24	- 5.31
RES	33.06	37.01	43.05	39.91	37.03

indicates a tendency for the model to overpredict the observed temperature. The magnitude of the RES in Table 3 suggests that there is a slight tendency for all of the methods to overpredict the observed temperature. By comparing RES and |RES|, the relatively small value of RES compared to |RES| suggests that the errors in the methods tend to cancel over the 24-h period of interest. In general, the large errors associated with all five methods would tend to mask any differences between the five methods so that for heat unit calculations all five are equally suitable.

Noteworthy in the use of these methods is that their accuracy was best on days with solar radiation $\geq 25 \text{ MJ m}^{-2} \text{ day}^{-1}$, defined as "clear days". The occurrence frequency of such days is limited in most temperate, subhumid to humid regions of the world. For example, in the north central part of the United States the mean probability of receiving at least $25 \text{ MJ m}^{-2} \text{ day}^{-1}$ between May and August is 40% or less (Baker and Klink, 1975; Baker et al., 1983). This suggests that temperature models requiring high radiation days for successful application may be providing questionable information more than one-half of the time.

While the overall sophistication for the various methods of calculating hourly temperatures from daily minimum or maximum varied, it is interesting to note that the simple approach of the SAWTOOTH model of Sanders (1975) showed essentially the same magnitude of errors when compared to the more complex sinusoidal models. The magnitude of the errors was not substantially different from any of the more sophisticated sine or cosine models. Ranking of the methods, based on the smallest error, showed either WAVE or WCALC to be the best under most circumstances. WEATHER generally had the largest error based on the 4-year averages and suggests the empirical relationship for determining the time of T_{MAX} may be site specific.

One of the objectives of this work was to determine the applicability of the selected methods in soyabean growth models for the upper mid-west of the U.S. The portability of the various methods is strongly dependent on the time of T_{MIN} and T_{MAX} assumed or calculated as a function of latitude and day or year or previously determined parameters and thus is site specific. The models

assuming fixed times of *TMIN* and *TMAX* will only be portable to other locations to the extent the assumptions hold. *WEATHER* attempts to be portable through use of an empirical equation that requires daily radiation. However, the empirical equation may require site calibration. *TEMP* also uses fitted parameters developed from local data that can vary from one location to another (Parton and Logan, 1981; Wann et al., 1985; Kimball and Bellamy, 1986). The best accuracy can be expected from those methods that are highly calibrated for a specific location, which may require as much work as direct measurement for a specific modeling effort. Thus, the proper selection for any location will require a compromise between the desired accuracy and ease of calibration with available data.

For process-oriented models, particularly those concerned with photosynthesis and transpiration, the midday performance on clear days is probably the most important criterion for these models. However, the limited number of clear days would suggest that improved methods should be developed for the partly cloudy days in the humid to subhumid mid-west. While there is considerable error shown in the estimation of hourly temperatures with these sub-routines that are currently used in soyabean growth models, the actual effects on the various processes within the model cannot be determined. The possible compensating effects, such as phloem loading or feedback inhibition of CO_2 fixation rates, within the plant growth models may not make the temperature calculations as sensitive as these results would indicate. However, in developing an accurate temperature model, the basic inputs to the model must be as accurate as possible and in line with the research objectives. The output of any plant growth model can be only as accurate as the input data. The results of this work showed hourly air temperatures were best estimated by *WAVE* that also had fewest site-specific assumptions and calibration factors.

SUMMARY

The selection of the best method depends on specific research objectives. For the most part, all methods gave reasonable estimates of hourly temperatures. The better agreement between observed and estimated temperatures on clear days is disconcerting in an area with many cloudy days. Despite the variability in the results from day to day for the more sophisticated methods, *WAVE* was the best method as indicated in the 4-year average statistics. *WAVE* had the lowest AME, RSME and $|\text{RES}|$ within a 24-h period and some of the least restrictive assumptions. *WCALC* was very close to *WAVE* when comparing the statistical parameters. For situations where simplicity is required, *SAWTOOTH* gave favorable results not far different from *WAVE*. *WEATHER* requires the additional input of daily solar radiation to calculate the time of *TMAX*, and *TEMP* requires coefficients that are a function of height and may be site specific. With site calibration, both *WEATHER* and *TEMP* may yield

better results. With the requirement for increased accuracy, direct measurement of hourly air temperature as input for plant growth models may be necessary.

ACKNOWLEDGEMENTS

The authors acknowledge the use of the experimental site provided by the West Central Experiment Station and the University of Minnesota and the computer subroutines provided by Drs. Basil Acock, Morris Huck and Gerritt Hoogenboom. The program for sunrise and sunset times was provided by G.J. Spoden and J.A. Zandlo. The editorial comments on model portability by Dr. Acock were appreciated.

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