CHAPTER 6

AIR TEMPERATURE MODEL EVALUATION AT EASTERN TROPICAL REGION

Abstract

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Abstract

Air temperature exerts a marked influence on plant growth and development. Most climatic stations mainly record the daily minimum and maximum temperatures. An attempt is made to determine the accuracy of several methods for calculating hourly air temperatures from their daily maxima and minima. Methods that have as inputs daily minimum and maximum air temperatures were selected from the literature. Three years of hourly air temperature data collected from 2007 October to 2010 June during the different season at screen height of 1.22 m over ground were used to test the various methods. Five days from each season for three years were randomly selected for detailed analysis. The results were compared with hourly data collected in the experimental site. Different statistical methods were used to determine the validity of each model. All methods worked reasonably well on clear days. The results also suggest that TM model performs better than the other models for all seasons during the study period.

6.1 Introduction

Temperature is one of the critical variables that drive all biological systems. Air temperature is a fundamental input parameter requirement 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 decrease at higher temperature. The development rate increases approximately linearly from a lower to an upper
threshold temperature. Temperature 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 development 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 are determined by first calculating degree-hours for each hour of the day. The number of degree-hours is calculated as the mean hourly temperature or the upper threshold, whichever is smaller, minus the lower threshold. To calculate degree-days, the degree-hours are summed over the 24-h day and the sum is divided by 24 (Snyder 1985).

For the validation of agricultural models and for climatological purposes, many of the available data consist of only the daily minimum and maximum temperatures. The hourly temperature data are often not available. For many models it is often useful to obtain an approximation of hourly temperature for a particular location and time of the year. Using measured hourly data offers the most accurate degree-hours and degree-days estimates, but maximum and minimum temperature data are often used to estimate degree-days by approximating diurnal temperature curves (Snyder et al 1999). 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; Floyd and Braddock 1984; Wann
et al 1985; De Gaetano and Knapp 1993; Yin et al 1995; Roltsch et al 1999) to more sophisticated techniques utilizing Fourier analysis (Carson 1963) and complex energy balance models (Carson and Moses 1963; Brown 1969; Lemon et al 1971). 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 Fourier series.

In the present study, an attempt has been made to determine the accuracy of several methods for calculating hourly air temperatures at screen height from their daily minima and maxima. Methods were selected that required limited inputs for calculating hourly air temperatures from their daily minima and maxima. The results were compared with hourly air temperature collected in the experimental site. Different statistical methods were used to determine the performance of each model.

6.2 Data and method

Details of the experimental site and collection of air temperature were given in Chapter 2. Air temperature recorded from 2007 October to 2010 June at one hour intervals at 1.22m above ground is used for the study. Five days from each season, for each year were randomly selected for detailed analysis. All air temperature 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.

WAVE Model

The first model (WAVE) was initially presented by De Wit et al (1978) and
was included in the subroutine WAVW 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 another cosine function from the time of the maximum temperature to the time of minimum temperature of the next day. The method fixes at 1400 hours the time of the maximum temperature, and at sunrise the time of the minimum temperature. The intervening temperatures are calculated from the following equations:

For \( 0 \leq H < \text{RISE} \) and \( 1400 \, h \leq H \leq 2400 \, h \)

\[
T(H) = T_{AVE} + AMP(\cos(\pi H'/(10 + \text{RISE})))
\]

...(6.1)

For \( \text{RISE} \leq H \leq 1400\, h \)

\[
T(H) = T_{AVE} - AMP(\cos(\pi (H - \text{RISE})/(14 - \text{RISE})))
\]

...(6.2)

where \( \text{RISE} \) 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 \( H < \text{RISE} \), \( H' = H-14 \) if \( H > 1400 \, h \) and \( T_{AVE} \) and \( AMP \) are defined as

\[
T_{AVE} = (T_{MIN} + T_{MAX})/2
\]

and

\[
AMP = (T_{MAX} - T_{MIN})/2
\]

respectively.

**WCALC Model**

The Wilkerson et al (1983) model (WCALC), included in the SOYGRO model V 5.3, 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. In addition to the current day’s \( T_{MAX} \) and \( T_{MIN} \), the method requires
the $T_{\text{MAX}}$ and $T_{\text{MIN}}$ of the previous day and the $T_{\text{MIN}}$ of the following day. The hourly temperatures are given by

(a) midnight to sunrise +2 h

$$T_{\text{AU}} = \pi \left( \frac{\text{SET}_{n-1} - \text{RISE}_{n-1} - 2}{\text{SET}_{n-1} - \text{RISE}_{n-1}} \right)$$

$$T_{\text{LIN}} = T_{\text{MIN}}_{n-1} + \left( T_{\text{MAX}}_{n-1} - T_{\text{MIN}}_{n-1} \right) \sin(T_{\text{AU}})$$

$$\text{SLOPE} = \frac{T_{\text{LIN}} - T_{\text{MIN}}_{n}}{\left( 24 - \text{SET}_{n-1} + \text{RISE}_{n} + 2 \right)}$$

$$T(H) = T_{\text{LIN}} - \text{SLOPE}(H + 24 - \text{SET}_{n-1})$$

(b) sunset to midnight

$$T_{\text{AU}} = \pi \left( \frac{\text{SET}_{n} - \text{RISE}_{n} - 2}{\text{SET}_{n} - \text{RISE}_{n}} \right)$$

$$T_{\text{LIN}} = T_{\text{MIN}}_{n} + \left( T_{\text{MAX}}_{n} - T_{\text{MIN}}_{n} \right) \sin(T_{\text{AU}})$$

$$\text{SLOPE} = \frac{T_{\text{LIN}} - T_{\text{MIN}}_{n+1}}{\left( 24 - \text{SET}_{n} + \text{RISE}_{n+1} + 2 \right)}$$

$$T(H) = T_{\text{LIN}} - \text{SLOPE}(H - \text{SET}_{n})$$

(c) daylight hours

$$T_{\text{AU}} = \pi \left( \frac{H - \text{RISE}_{n} - 2}{\text{SET}_{n} - \text{RISE}_{n}} \right)$$

$$T(H) = T_{\text{MIN}}_{n} + \left( T_{\text{MAX}}_{n} - T_{\text{MIN}}_{n} \right) \sin(T_{\text{AU}})$$

...(6.3)

...(6.4)

...(6.5)

where

TAU, TLIN, SLOPE are temporary variables in calculation.

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

**Double cosine model**

A deterministic model to calculate the daily mean air temperature profile is the double cosine model, which is recommended by the National Meteorological Institute of Portugal and uses three sinusoidal segments to connect the times of occurrence of
the daily maximum and minimum air temperatures (Bilbao et al. 2002). The model is
given by the following expressions:

\[
T(y,m,d,t) = T(y,m,d) - \cos \left( \frac{\pi(t_{T_{min}} - t)}{24 + t_{T_{min}} - t_{T_{max}}} \right) \frac{A_{T}(y,m,d)}{2} \quad \ldots (6.6)
\]

\[1 \leq t \leq t_{T_{min}},\]

\[
T(y,m,d,t) = T(y,m,d) + \cos \left( \frac{\pi(t_{T_{max}} - t)}{24 + t_{T_{max}} - t_{T_{min}}} \right) \frac{A_{T}(y,m,d)}{2} \quad \ldots (6.7)
\]

\[t_{T_{min}} \leq t \leq t_{T_{max}}, \text{ and} \]

\[
T(y,m,d,t) = T(y,m,d) - \cos \left( \frac{\pi(24 + t_{T_{min}} - t)}{24 + t_{T_{min}} - t_{T_{max}}} \right) \frac{A_{T}(y,m,d)}{2} \quad \ldots (6.8)
\]

\[t_{T_{max}} \leq t \leq 24,\]

where \(T(y,m,d)\) is the daily mean air temperature, \(A_{T}(y,m,d)\) is the daily thermal amplitude (°C), \(t_{T_{min}}\) is the hour at which the hourly minimum temperature occurs, \(t_{T_{max}}\) is the hour at which the hourly maximum temperature occurs, and \(t\) is the hour of the day.

**TM Model**

TM model developed by Carla et al. (2001) uses two sine-wave functions in the daylight and a square-root decrease in temperature at night. It divides day into three segments: from the sunrise hour \(H_{n}\) to the time of maximum air temperature \(H_{x}\), from \(H_{x}\) to the sunset hour \(H_{o}\), and from \(H_{o}\) to the sunrise hour for the next day \(H_{p}\). \(T_{n}\), \(T_{x}\) and \(T_{0}\) denote the minimum, maximum and sunset hour air temperature on the current day and \(T_{p}\) is the minimum on the following day. \(H_{n}\) 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 (\( H_x = H_0 - 4 \)).

The temperatures at \( H_n(T_n) \), \( H_x(T_x) \), and \( H_p(T_p) \) are input. For a given \( T_n \), \( T_x \) and \( T_p \) as well as \( T_0 \), the TM model calculates the hourly temperature \( T(t) \) according to the following equations:

\[
T(t) = T_n + \alpha \left[ \left( \frac{t - H_n}{H_x - H_n} \right) \frac{\pi}{2} \right], \quad H_n < t \leq H_x \quad \cdots (6.9)
\]

\[
T(t) = T_0 + R' \sin \left[ \frac{\pi}{2} + \left( \frac{t - H_x}{4} \right) \frac{\pi}{2} \right], \quad H_x < t < H_0 \quad \cdots (6.10)
\]

\[
T(t) = T_0 + b \sqrt{t - H_0}, \quad H_0 < t \leq H_p \quad \cdots (6.11)
\]

In the above equations, \( t \) is the hour of the day in standard time, and \( \alpha, R', \) and \( b \) are given by

\[
\alpha = T_x - T_n
\]

\[
R' = T_x - T_0
\]

\[
b = \frac{T_p - T_0}{\sqrt{H_p - H_0}}
\]

6.3 Results and discussion

6.3.1 Model evaluation on randomly selected days

Most of the climatological stations record mainly the daily maxima and minima temperatures but do not register hourly temperatures, several research efforts were made to model the daily behaviour of air temperature. The shape of the diurnal temperature curve has been modeled with a variety of methods with varying degrees
of complexity. The linear and simple curve models have an advantage in that they are easy to use and often require only daily minimum and maximum temperatures.

In the present study, the data for the random days were grouped and analyzed using the three year (October 2007 to June 2010) means of various error parameters to draw conclusions about the accuracy of each method with selected examples. An example where all the methods for calculating hourly temperatures worked reasonably well is illustrated in figure 6.1. This date (DOY 25, 2009) was selected because the diurnal trend was smooth throughout the 24-hour period and the range between maximum (41.6°C) and minimum (17.9°C) was large (23.7°C). The calculated results for all models are reasonably close to the observed values. However, there are differences between the observed and estimated temperatures for each of the methods.

Figure 6.1 Hourly temperatures calculated by the four methods versus time compared with observed data for a randomly selected DOY 25, 2009, for which the difference between $T_{MAX}$ and $T_{MIN}$ was 23.7°C.
The magnitude of the errors with each of the methods seems to change through the 24-hour period and is most easily noted by plotting the hourly error, i.e., the difference between the observed temperature ($T_o$) and the estimated temperatures ($T_e$) in figure 6.2 for the same day. As expected, the difference between $T_e$ and $T_o$ is smallest at about hour 7 and 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 10 °C, with the time of maximum error varying among the different methods.

Figure 6.2 Summary of the time trend of the difference between the estimated and observed temperatures for each of the methods on DOY 25, 2009

In this work, to test the accuracy of the various models, air temperature measured at hourly intervals were compared to the calculated values over a 24 hour period. The goodness of fit of each of the models was assessed in several ways.
a) The absolute mean error (AME)

AME is the sum of the absolute values of differences between the estimated \( T_c \) and observed \( T_o \) temperatures at any time:

\[
AME = \frac{\sum_{i=1}^{n} |T_{e_i} - T_{o_i}|}{n}
\]

where \( n \) is the number of observations.

(b) The root mean square error (RMSE)

RMSE is calculated to reflect the overall accuracy of the shape of the predicted curve.

\[
RMSE = \left[ \frac{\sum_{i=1}^{n} (T_{o_i} - T_{e_i})^2}{n} \right]^{1/2}
\]

The closer the estimated temperatures are to the observed temperature, the smaller the RMSE.

(c) The sum of the residuals (RES) and the sum of the absolute residuals, \(|RES|\)

The sum of the residuals (RES) and the sum of the absolute value of the residuals \(|RES|\) were used to evaluate how consistent the models were in calculating air temperature throughout daily cycle.

\[
RES = \sum_{i=1}^{n} (T_{o_i} - T_{e_i})
\]

\[
|RES| = \sum_{i=1}^{n} |T_{e_i} - T_{o_i}|
\]

A value of RES close to zero indicates an unbiased model and smaller values of absolute value of the residuals indicate better performance. These statistics are useful.
to determine the tendency to over predict or under predict the temperature over a period of time.

(d) The determination coefficient or squared correlation coefficient, $R^2$

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (T_{o_i} - T_{e_i})^2}{\sum_{i=1}^{n} (T_{o_i} - \bar{T}_{o_i})^2}$$  \hspace{1cm} \text{(6.16)}$$

where $\bar{T}_{o_i}$ is the mean of $T_{o_i}$, $i = 1,2, \ldots, n$.

The error analysis for DOY 25, 2009 shown in figures 6.1 and 6.2 is summarized in Table 6.1. The RMSE varied from a low of 2.15 for TM to 4.59 for Double cosine. The AME varied from a low of 1.83 to 3.33 for the same methods. The correlation coefficient $R^2$ varied from a low of 0.63 for Double cosine to a high of 0.92 for TM, suggesting reasonable fit, based on the overall diurnal trend. The RES and $|RES|$ show relatively small numbers.

Table 6.1 Summary of the statistics for DOY 25, 2009, illustrating the magnitude of the errors

<table>
<thead>
<tr>
<th>Statistics</th>
<th>WAVE</th>
<th>WCALC</th>
<th>TM</th>
<th>DOUBLE COSINE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R^2$</td>
<td>0.64</td>
<td>0.83</td>
<td>0.92</td>
<td>0.63</td>
</tr>
<tr>
<td>AME</td>
<td>3.21</td>
<td>2.68</td>
<td>1.83</td>
<td>3.33</td>
</tr>
<tr>
<td>RMSE</td>
<td>4.49</td>
<td>3.11</td>
<td>2.15</td>
<td>4.59</td>
</tr>
<tr>
<td>RES</td>
<td>-44.44</td>
<td>-15.06</td>
<td>-19.84</td>
<td>-75.49</td>
</tr>
<tr>
<td>$</td>
<td>RES</td>
<td>$</td>
<td>75.82</td>
<td>63.86</td>
</tr>
</tbody>
</table>
As a second example, DOY 327, 2008 is selected. This day's data were selected to illustrate the fit of all the methods for calculating hourly temperatures. There was not a smooth trend in the observed temperatures and only a small difference (9.8°C) between the $T_{\text{MAX}}$ (31.6°C) and $T_{\text{MIN}}$ (21.8°C). This small range of temperatures resulted in relatively small errors on an absolute basis. The largest difference between $T_e$ and $T_o$ was 4.7°C for Double cosine shown in figure 6.4.

As in the DOY 25, 2009 data, the minimum errors are associated with the time of $T_{\text{MIN}}$ and $T_{\text{MAX}}$. 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.

Figure 6.3 Summary of hourly temperatures calculated by the four methods on DOY 327, 2008, versus time representing one of the randomly-selected days for which the difference between $T_{\text{MAX}}$ and $T_{\text{MIN}}$ was 9.8°C.
Figure 6.4 Summary of the time trend of the difference between the estimated and the observed temperature for each of the methods on DOY 327, 2008.

Table 6.2 Summary of the statistics for DOY 327, 2008, illustrating the magnitude of the errors.

<table>
<thead>
<tr>
<th>Statistics</th>
<th>WAVE</th>
<th>WCALC</th>
<th>TM</th>
<th>DOUBLE COSINE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R^2$</td>
<td>0.67</td>
<td>0.72</td>
<td>0.84</td>
<td>0.63</td>
</tr>
<tr>
<td>AME</td>
<td>1.18</td>
<td>1.31</td>
<td>0.84</td>
<td>1.38</td>
</tr>
<tr>
<td>RMSE</td>
<td>1.64</td>
<td>1.52</td>
<td>1.17</td>
<td>1.74</td>
</tr>
<tr>
<td>RES</td>
<td>-24.52</td>
<td>-27.08</td>
<td>-17.63</td>
<td>-29.21</td>
</tr>
<tr>
<td>$</td>
<td>RES</td>
<td>$</td>
<td>30.03</td>
<td>33.02</td>
</tr>
</tbody>
</table>
The error parameters for DOY 327, 2008 are summarized in Table 6.2. The $R^2$ ranges from the low of 0.63 for Double cosine to a high of 0.84 for TM. The AME ranged from 0.84 to 1.38 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 DOY 25, 2009, the RES and $|RES|$ were smaller, due to the small spread between the maximum and minimum temperature.

6.3.2 Model evaluation on different seasons

To calculate the accuracy of the calculation methods in fitting the diurnal temperature fluctuations within a 24-hour period, five days from each season were randomly selected from 2007 October to 2010 June. The three year mean $R^2$ values for the 15 random days of each season are calculated. Analysis of the days selected on the basis of seasons showed that all models had a somewhat lower accuracy ($R^2$) at south west monsoon and north east monsoon. The accuracy of all the models showed a better performance at pre-monsoon and winter. 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. On overcast days, factors other than radiation assume more importance in determining air temperature, altering the shape of the diurnal temperature curve.

Reicosky et al (1989) have determined the accuracy of different models selected from the literature based on their simplicity. All methods worked well on clear days, but had limited success on overcast days. They concluded that, with the requirement for increased accuracy, direct measurement of hourly air temperature as input for plant growth models may be necessary.
6.3.3 Overall comparison

The three year mean statistics for the sixty random days are summarized in Table 6.3 for each of the four methods. The $R^2$ values ranged from a low of 0.60 for WAVE to a high of 0.79 for TM. The lowest RMSE value was obtained for the TM model and the largest for WAVE model. By comparing RES to $|RES|$, one can determine how well the error in the model will cancel over a period of time for integrated degree-hour calculations.

The TM model was developed by Carla et al (2001) 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 temperature model gave good results, the root mean square error being less than 2 °C for most years and locations. In this case, the best overall prediction was obtained at non coastal region where as small RMSE values at costal location.

A large positive RES that approaches $|RES|$ suggests that the model consistently underestimated the observed temperature. A large negative RES in comparison with $|RES|$ indicates a tendency for the model to over predict the observed temperature. The performances of the WCALC and double cosine models were similar in terms of RMSE and $|RES|$, showing overestimation. The small RES values show a tendency for the TM model to overestimate the observed temperature and the comparison of $|RES|$ suggest that the error in the method tend to cancel-out over the daily period.

Table 6.3 Summary of the three year mean statistics for the randomly-selected days

<table>
<thead>
<tr>
<th>Statistics</th>
<th>WAVE</th>
<th>WCALC</th>
<th>TM</th>
<th>DOUBLE COSINE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R^2$</td>
<td>0.60</td>
<td>0.62</td>
<td>0.79</td>
<td>0.64</td>
</tr>
<tr>
<td>AME</td>
<td>1.99</td>
<td>2.02</td>
<td>1.39</td>
<td>1.87</td>
</tr>
<tr>
<td>RMSE</td>
<td>2.75</td>
<td>2.33</td>
<td>1.76</td>
<td>2.53</td>
</tr>
<tr>
<td>RES</td>
<td>-30.27</td>
<td>-23.94</td>
<td>-5.39</td>
<td>-29.56</td>
</tr>
<tr>
<td>$</td>
<td>RES</td>
<td>$</td>
<td>49.18</td>
<td>48.78</td>
</tr>
</tbody>
</table>

152
The models were also analyzed for accuracy by season. The error analysis for the data obtained from each model on the basis of the season presented in figure 6.5 showed very little difference between the performances in different seasons for the TM model, which gave consistently the best accuracy. The reason for this difference is attributed to clouds and variable winds at the location, which alter the classic shape of the diurnal radiation and temperature curves. 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 coastal area.

6.4 Conclusions

- Four air temperature models viz., WAVE, WCALC, TM DOUBLE and COSINE were used for calculating hourly air temperatures from daily maxima and minima. The accuracy of the four different models was evaluated and assessed by means of widely used statistics: AME, RMSE, RES, $|RES|$ and $R^2$. All models worked reasonably well on clear days.

- Analysis of the days selected on the basis of seasons showed that all models had a somewhat lower accuracy ($R^2$) at south west monsoon and north east monsoon. The accuracy of all the models showed a better performance at pre-monsoon and winter.

- In comparing the RMSE relative values, it can be observed that the TM model obtains smaller relative error values. The results in this study suggest that the TM model is a simple and accurate method to approximate the daily air temperature curve from maximum and minimum daily temperature.
Among the models that calculate daily air temperature, the TM model is the most recommended, because it is the best in reproducing the statistical characteristics of data in all seasons.

The results can be used in different scientific areas such as solar climatology, renewable solar energy simulation and design, energy-efficiency studies, and solar-energy engineering applications, as well as in other scientific fields for which air temperature data, in different timescales, are required as input for important system simulations. It is for the first time air temperature model evaluation is carried out in eastern tropical region. When accuracy of temperature input to crop simulation models is critical, direct measurement of hourly air temperature may be necessary.