

Analytical Modeling for Predicting Soil Temperature for Bare and Mulched Soil in Arid Region

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Abstract

An analytical truncated sinusoidal (TS) model based on sine solution to the conduction of soil heat was designed for predicting daytime soil temperature. Daytime hourly soil temperature from 0500 to 2000 h were recorded with YSI tele thermometer for air, bare soil, wheat straw mulched, and neem leaves mulched sandy soil at different depths. The TS model performed better than conventional sinusoidal (CS) model in bare and mulched conditions. The values of mean relative deviation (\bar{Y}) between the predicted and observed temperatures were less than 10% in case of TS but more than 10% in case of CS in bare and mulched conditions. The results indicate that the analytical model is practically feasible as it requires easily measurable input parameters for predicting bare and mulched soil temperatures.

Key words : Analytical model, Mulch, Soil temperature, Temperature model.

Modeling of soil temperature is important not only for reducing the cost and time spent in recording temperature but also for optimizing thermal regime of arid regions. The diurnal air and soil temperatures have been modeled through empirical models (1), analytical sine wave models (2—4), and numerical models (5, 6) at bare and mulched soil conditions with various degree of complexities and successes. Although the numerical models have potential to predict the diurnal soil temperatures with more accuracy than those of analytical models but require high input of technology which is not always available in remote areas. On the other hand, the use of analytical models is simple and easy, as analytical models require easily measurable input data. Under simplified initial boundary conditions, analytical truncated sine models (7, 8) have been found to be more accurate than the conventional sinusoidal (CS) model (9). Wilkerson et al. (8) used temperature model WCALC to predict the air temperature by dividing the day into three segments. Parton and Logan (7) gave a temperature model TEMP that divided the day into two segments and utilized a truncated sine wave for the daytime and exponential decrease for nighttime to predict air and soil temperatures. To our knowledge, information on prediction of daytime soil temperature under mulched conditions using analytical truncated models is scanty. Therefore, the study was carried

out with the objective to design an analytical truncated sinusoidal model based on easily measurable input temperature data for predicting daytime soil temperature for bare and mulched soil conditions.

Theory

Basic Equation

The conduction of soil heat in one-dimensional downward z -direction is given as :

$$\frac{\partial T}{\partial t} = - \frac{\partial}{\partial z} \left(D \frac{\partial T}{\partial z} \right) \quad \dots(1)$$

where T is temperature at time t and depth z , and D is thermal diffusivity which is ratio of thermal conductivity (λ) to volumetric heat capacity (ρc). Assuming that D remains constant with depth and time, Eq. (1) can be rewritten as :

$$\frac{\partial T}{\partial t} = D \frac{\partial^2 T}{\partial z^2} \quad \dots(2)$$

Using separation of variable technique and following boundary conditions,

Table 1. Parameters and results of analytical temperature models. WM=wheat straw mulch, NM=neem leaves mulch, DOM=date of esurement, T_{av} =average soil surface temperature, A_0 =amplitude of soil surface temperature variations, t_{max} =time at which temperature reaches to maximum value, # = experimental t_{max} , ## = estimated t_{max} at $p = 16$ h, p = time period, \bar{Y} =mean relative deviation, TS=truncated sinusoidal model, CS=conventional sinusoidal model.

Surface condition	D O M	Soil depth/ height (cm)	T_{av} (°C)	A_0 (°C)	t_{max} (h)	\bar{Y} (%)		
						TS (p=16 h)	CS (p=24 h)	
1	Air	7. 2. 99	100	17.0	11.0	14.0#	8.9	34.9
2		26. 4. 99	100	34.7	8.2	13.0#	7.4	19.7
3	Bare	26. 4. 99	0	35.5	12.7	13.0#	8.0	13.6
4		26. 4. 99	5	35.5	-	13.6# #	7.2	10.5
5		7. 2. 99	0	18.6	11.9	14.0#	4.1	34.3
6		7. 2. 99	5	18.6	-	14.6# #	7.7	31.7
7	WM	26.4. 99	0	34.5	11.5	13.0#	6.0	12.0
8		26. 4. 99	5	34.5	-	14.4# #	4.0	11.3
9		7. 2. 99	0	20.0	13.0	14.0#	7.4	38.8
10		7. 2. 99	5	20.0	-	15.4# #	9.6	19.6
11	NM	26.4. 99	0	35.0	12.0	13.0#	6.0	11.9
12		26. 4. 99	5	35.0	-	14.1# #	3.1	10.4
13		7. 2. 99	0	19.0	11.0	14.0#	7.1	31.1
14		7.2. 99	5	19.0	-	15.1# #	7.5	19.3

$$T(z, t) = T_{av} + A_0 \sin \omega t \quad \text{for } z = 0, t > 0 \quad \dots(3)$$

$$\lim_{z \rightarrow \infty} T(z, t) = T_{av} \quad \dots(4)$$

where T_{av} is average soil temperature, A_0 is amplitude of the sinusoidal soil temperature variations at soil surface, $\omega = 2\pi/p$, and p is the time period of the day.

According to Kirkham and Power (9), sinusoidal solution of Eq. (2) is given as :

$$T(z, t) = T_{av} + A_0 [e^{-(\omega/2D)^{1/2}z}] \sin [\omega t - (\omega/2D)^{1/2}z + \phi] \quad \dots(5)$$

where ϕ is phase constant, which is added to account the phase difference between predicted (Eq. 5) and measured diurnal soil temperature. The Eq. (5) predicting the diurnal soil temperature variations for $p=24$ h is termed as conventional sinusoidal (CS)

Table 2. Relevant properties of the experimental soil and mulching materials. A_0 =amplitude of temperature variations at surface, A_z =amplitude of temperature variations at given depth, DD=damping depth, D=thermal diffusivity.

Soil/material	Soil depth (cm)	A_0 (°C)	A_z (°C)	DD (cm)	D (cm ² /h)
Sand	0-5	14.4	11.8	25.0	81.8
	0-10	14.4	6.4	12.3	19.8
Wheat straw	0-5	12.3	8.0	11.5	17.3
Neem leaves	0-5	11.7	8.2	14.0	25.6

model in the present study.

Diurnal temperature variations had not followed the sinusoidal pattern exactly (9), therefore, an analytical truncated sinusoidal solution with $p < 24$ h (Eq. 5) was used to predict the daytime soil temperature.

Model Description

An analytical truncated sinusoidal (TS) model

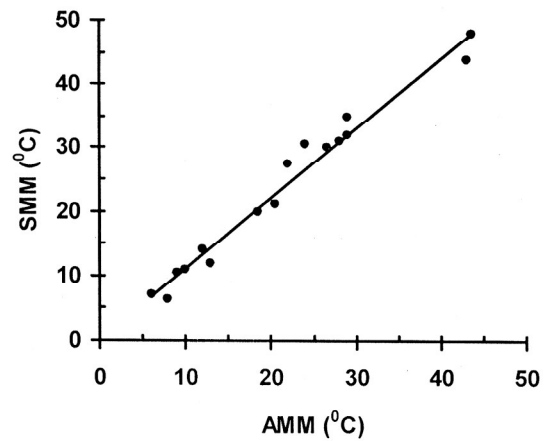


Figure 1. Relationship between maximum and minimum soil surface temperatures (AMM), and maximum and minimum air temperatures (AMM) at Regional Research Station, Balsamand.

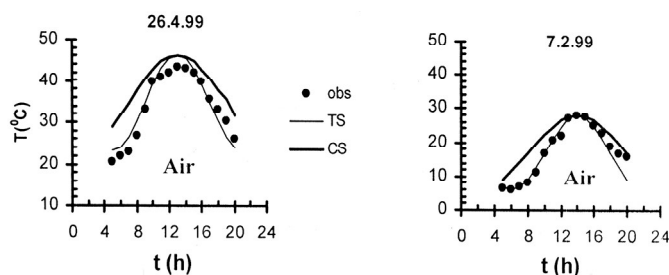


Figure 2. Observed and predicted daytime air (1 m height) temperature using truncated sinusoidal (TS) and conventional sinusoidal (CS) models on 7. 2. 99 and 26. 4. 99.

was designed for optimized time period (p) equal to 16 h. For designing the TS model, first analytical solution (Eq. 5) was used for predicting daytime air (1 m height) temperatures ($5 < t < 20$ h) for p equal to 14, 15, 16 and 17 h, and then optimized it for p equal to 16 h from close matching of predicted temperatures to the observed temperatures (Fig. 1) and minimum value of mean relative deviation (\bar{Y}) between predicted and observed temperatures (Table 1). For the sake of brevity, only the values of \bar{Y} for p equal to 16 h are shown.

It is pertinent to point out that optimum time period may vary according to latitude of the experimental site.

The average soil temperature (T_{av}) in the TS and CS models was assumed to be constant with depth and estimated from Van Wijk et al. (10) relation :

$$T_{av} = (T_{max} + T_{min})/2 \quad \dots(6)$$

where T_{max} and T_{min} are maximum and minimum tem-

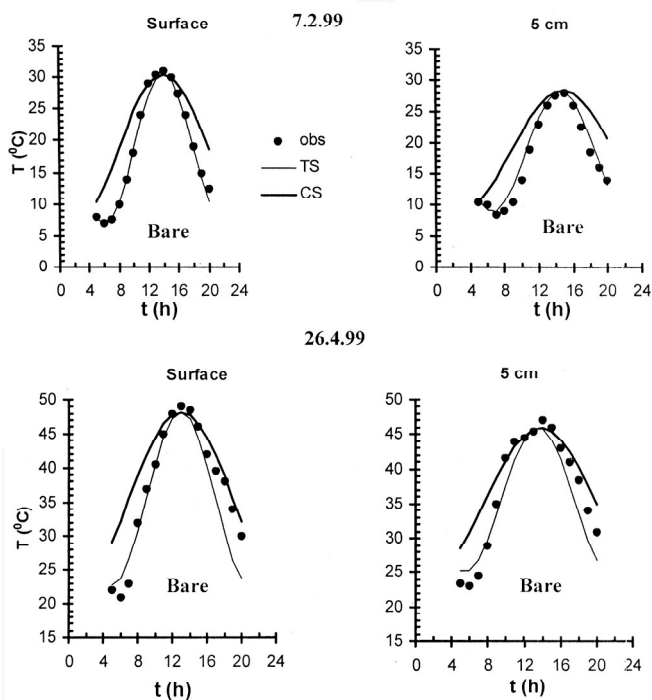


Figure 3. Observed and predicted daytime soil temperature using truncated sinusoidal (TS) and conventional sinusoidal (CS) model for bare soil at indicated depths on 7. 2. 99 and 26. 4. 99.

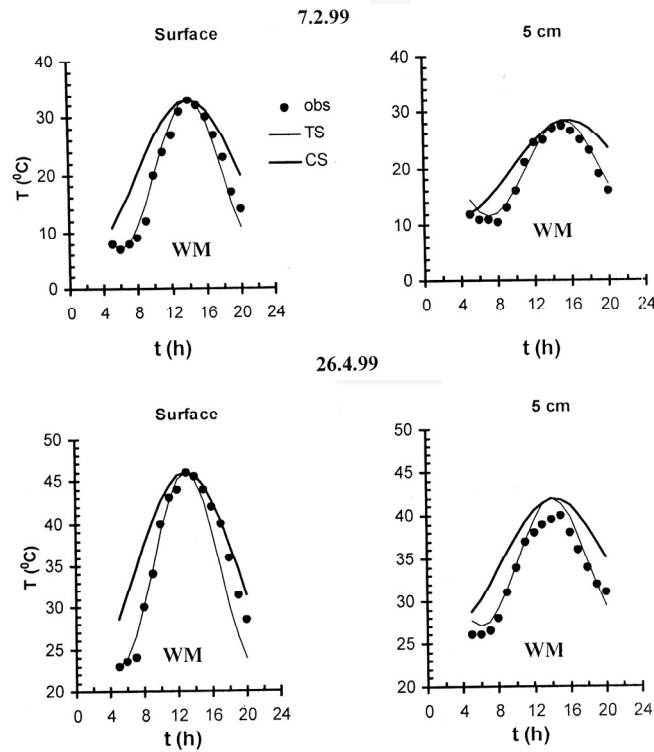


Figure 4. Observed and predicted daytime soil temperature using truncated sinusoidal (TS) and conventional sinusoidal (CS) model for neem leaves mulched (NM) soil at indicated depth on 7. 2. 99 and 26.4. 99.

peratures of soil surface. These were measured experimentally for mulched surface and estimated for bare soil from air temperatures through an empirical relation (Eq. 12) between air and soil surface temperatures. The thermal diffusivity (D) was estimated from damping depth (DD) using Carshaw and Jaeger (11) relation :

$$D = (DD)^2\omega/2 \quad \dots(7)$$

The damping depth is the depth at which amplitude of soil temperature wave becomes $1/e$ times of the amplitude of temperature wave at soil surface. The DD was determined using Van Wijk et al. (10) relation :

$$DD = (z_2 - z_1) / (\ln A_1 - \ln A_2) \quad \dots(8)$$

where A_1 and A_2 are amplitudes of soil temperature variations at depth z_1 and z_2 , respectively. The phase constant (ϕ) is determined using Eq. (3) from the time (t_{max}) at which temperature reaches to maximum value :

$$\sin(\omega t_{max} + \phi) = 1 \quad \dots(9)$$

The t_{max} is determined using Jackson and Kirkham (12) method :

$$t_{max 2} - t_{max 1} = \left[\frac{p(z_2 - z_1)^2}{4\pi D} \right]^{1/2} \quad \dots(10)$$

where $t_{max 1}$ and $t_{max 2}$ are the time at which temperature reaches to maximum value at surface ($z_1 = 0$) and depth z_2 , respectively.

Methods

Daytime hourly temperatures from 0500 to 2000 h were measured using YSI tele thermometer on 7. 2. 99 and 26.4. 99 for air (1 m height), bare soil, wheat straw mulch (WM), and neem leaves mulch (NM) at surface and 5 soil depth at Regional Research Station Balsamand (35 km west of Hisar) of Chaudhary Charan

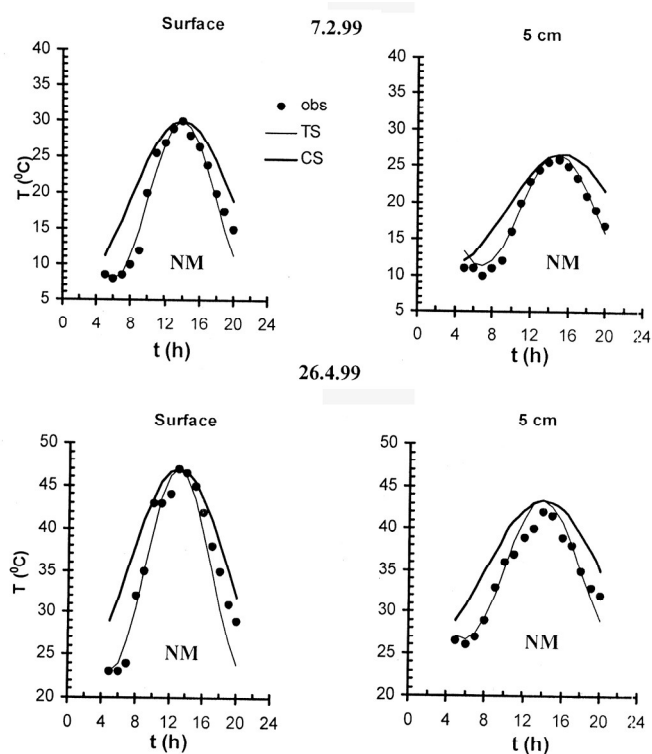


Figure 5. Observed and predicted daytime soil temperature using truncated sinusoidal (TS) and conventional sinusoidal (CS) model for neem leaves mulched (NM) soil at indicated depths on 7. 2. 99 and 26.. 4. 99.

Singh Haryana Agricultural University (29° 07' N, 75° 28' E, 225 m elevation), Hisar, Haryana. The experimental soil was sand (92.2% sand, 5.3% silt, and 2.5% clay) and classified as Torripsamment according to Soil Survey Staff (13). The surface temperatures were measured by placing the sensor just 5 mm below the soil/mulch surface in order to avoid the reflected heat radiation effect. The temperatures were measured at three randomly selected places in the observation plot (1 × 1 m). The plots were bound by an iron mesh boundary of 8 cm in height, half of which was embedded in the soil to minimize the shadow effect. In mulched plots, temperatures were recorded after 10 days of mulch application. The thickness of neem leaves and wheat straw mulch (approximately 2 cm long) was 5 cm, equivalent to 19 Mg/ha and 56 Mg/ha, respectively on dry weight basis. The thermal diffusivity for soil and mulching materials was estimated from damping depth (DD) using Eq. (7) and DD

was determined from the amplitude of soil temperature measured at different depths (Eq. 8). The amplitude is determined from maximum and minimum soil temperatures measured at surface, 5 and 10 cm depths on 25. 4. 99 (Table 2). Thermal diffusivity and damping depth of soil and mulching materials are given in Table 2. The accuracy of the model was tested using mean relative deviation (\bar{Y}) between predicted and observed temperatures as :

$$\bar{Y} = \frac{1}{N} \sum_{i=1}^N |Y_i| \quad \dots(11)$$

where Y_i is the relative percent deviation of the i th predicted temperature from the observed one, and N is the total no. of observations.

Results and Discussion

Soil surface maximum and minimum (SMM) tem-

peratures were found linearly related to respective air maximum and minimum (AMM) temperatures for bare soil (Fig. 2) as :

$$\text{SMM} = 1.1037(\text{AMM}) + 0.1516, R^2 = 0.97 \quad \dots(12)$$

The SMM estimated using Eq. (12) from AMM will be used as the input parameter in the truncated sinusoidal (TS) model. Linear empirical relation between air and soil surface temperatures had also been established in earlier studies with fair degree of success (14, 15). However, in mulch treatments, experimental surface temperatures were used since no such relationship between SMM and AMM could be established in the individual mulch due to lack of sufficient data.

The designated TS model accurately predicted daytime temperature of bare soil, WM and NM mulched soil at surface and 5 cm depth on 7. 2. 99 and 26. 4. 99 with mean relative deviation (\bar{Y}) values less than 10% (Table 1). The TS model also performed better than the conventional sinusoidal (CS) model for predicting daytime temperatures for bare soil, WM and NM mulched soil at surface and 5 cm depth on 7. 2. 99 and 26. 4. 99. The \bar{Y} values were more than 10% in CS model for bare soil, WM and NM mulched soil (Table 1). Further, the close matching of predicted daytime soil temperatures with those of observed temperatures (Figs. 3, 4 and 5) verified the validity of the designed TS model for bare and mulched soil at surface and 5 cm depth in arid region.

Conclusion

An analytical truncated sinusoidal (TS) model for time period equal to 16 h was designed. An empirical relationship established between maximum and minimum soil surface and air temperatures might be used to obtain the maximum and minimum soil surface temperatures for the experimental sandy soil under bare condition. The TS model accurately predicted the daytime soil temperatures at bare and mulched soil conditions at surface and 5 cm depth on 7. 2. 99 (winter) and 26. 4. 99 (summer) with \bar{Y} values less than 10%. The TS model also predicted daytime soil temperature more accurately than conventional sinu-

soidal model in the present study. The performance of the TS model indicates that the truncated model has potential for predicting bare and mulched soil temperatures using easily measurable input parameters.

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