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A simple model to estimate air temperature and soil temperatures under vertisol

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सार—साइन वक्र और चरघातांकी फलन मॉडलों के आधार पर क्रमशः दिन और रात में वायु और मृदा के तापमान में दैनिक परिवर्तनों का आकलन किया गया है । प्रत्येक मॉडल में केवल चार प्राचलों का उपयोग किया गया है, उदाहरणार्थ विभिन्न तलों पर अधिकतम और न्यूनतम तापमान, सूर्यास्त का समय तथा दिन/रात की अवधि । जब इन मॉडलों का अनुप्रयोग प्रयोगात्मक और स्वतंत्र आंकड़ा समुच्चयों पर किया जाता है तो इनसे, 1430 बजे तथा पृथ्वी पर सूर्यास्त के समय के बीच की अवधि को छोड़कर, दिन और रात के किसी भी समय के लिए काफी हद तक सही आलकलन प्राप्त होता है ।

ABSTRACT. Based on a truncated sine curve and exponential function models, diurnal changes in air and soil temperatures have been estimated during day and night hours respectively. Each model uses only four parameters, *viz.*, maximum and minimum temperature at various levels, the time of sunset and duration of day/night length. The models, when applied to experimental as well as independent data sets, were found to give reasonably accurate estimates for any time of the day and night except between 1430 IST and sunset at the ground surface.

Key words — Sine curve, Exponential function, Thermal conductivity, Diurnal, Sunset, Day length, Absolute error.

1. Introduction

Among the many agro-meteorological factors that control microbiological activities of the plant, contribution of soil temperature is, perhaps, the largest. The soil temperature affects the plant at all its stages from seed germination to its physiological maturity. For instance, unless an optimum thermal regime is available, germination of the seeds is retarded significantly. The functional activity of the plant roots, such as, absorption of water and nutrients, are affected both at high and low temperature. Direct *in situ* monitoring of soil temperature is of great value to agriculture. Soil temperature, alongwith soil moisture and their life-cycle are important during many agricultural activities. For instance, in temperate latitudes, potato lifting season work has to be postponed or discontinued if the soil temperature at 10 cm depth falls below a certain minimum so as to prevent damages to the crop (Roodenburg 1985). Since soil temperatures are recorded at some time interval at very few locations, there is a need to estimate reasonably accurate soil temperatures at various depths at any time of the day.

In the present study, an attempt has been made to obtain the soil temperatures at various depths from corresponding maximum and minimum soil temperatures. Similarly, air temperature has also been estimated.

2. Data used

The study utilises experimental data from 23 November to 8 December 1989, recorded with conventional thermometers within 2000 sq m area in Central Agrimet. Observatory, Pune. The experimental site was surrounded by agricultural field. The soil of the site and surrounding area was black in texture with heat capacity of 3.35×10^3 J/K/kg. In the experiment, soil temperatures at the ground surface, 5, 10, 15, 20 and 30 cm depth were observed at 3-hour interval. These observations were taken manually at 3-hr interval, *viz.*, 0230, 0530,......, 2330 IST on bare soil. Air temperature was also measured at Stevenson screen level (*i.e.*, 122 cm agl) by conventional thermometer.

3. Model used

A number of models have been developed in recent years on the impact of soil temperature on crop growth (Watanabe 1978, Meikle and Gilchrist 1983). Goudrian and Waggoner (1972) calculated the energy budget at the crop canopy and soil temperature. Parton and Logan (1981) used the Fourier heat conduction model to predict soil temperature as a function of soil surface temperature. Diurnal variations in soil and air temperatures have been studied by Johnson and Fitzpatrick [1977 (a & b)] using sinusoidal model.

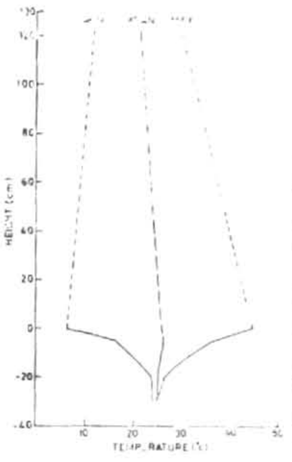
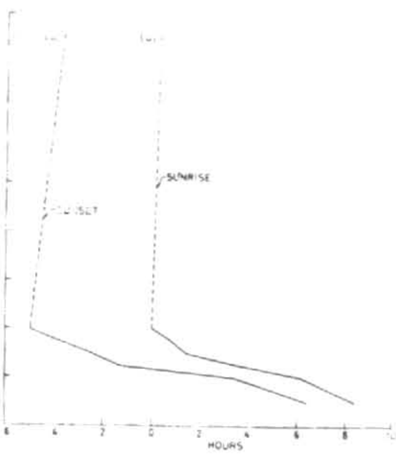


Fig. 1. Daily average maximum, minimum and mean air temperature and temperature at different soil depths



Figs. 2 (a & b). Time lag between occurrence of : (a) min. temp. with respect to sunrise time and (b) max. temp. with respect to sunset time

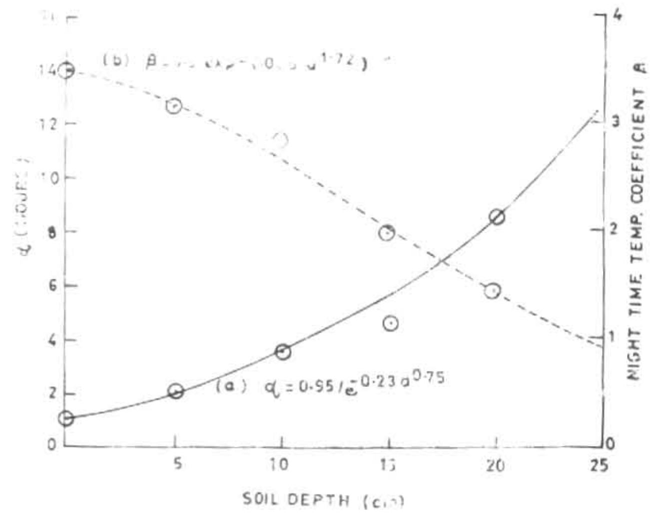


Fig. 3. Variation of α and β with soil depth

The present paper uses a truncated sine curve to predict day time air and soil temperature variations and an exponential function to estimate temperature changes during the night. The model has been earlier adopted by Parton and Logan (1981) for estimating diurnal variations in soil and air temperatures at Denver (Colorado), USA. According to the present model if T_x and T_n are the maximum and minimum air/soil temperatures respectively, D is the day length, and m, the number of hours after the occurrence of minimum temperature until sunset, then the temperature at the i th hour during the day time is described by :

$$T_i = (T_x - T_n) \sin [\pi m/(D+2\alpha)] + T_n \quad (1)$$

where, α (in hours) is the coefficient of day time temperature. Similarly, the temperature during the night hours is given by :

$$T_i = (T_s - T_n) \exp -(\beta n/N) + T_n \quad (2)$$

where, T_s is the temperature at sunset, n the number of hours after sunset till the time of occurrence of minimum soil/air temperature, N is the duration (hours) of the night and β the night time temperature coefficient. T_s is calculated with Eqn. (1). The coefficient β controls the temperature decrease during night.

The model is based of the following assumptions :

(*i*) The maximum temperature, either of soil or air, is attained during day time hours;

(*ii*) Similarly, the minimum temperature occurs just before or after sunrise; and

(*iii*) Diurnal variations of the soil temperature are considerable upto 20 cm depth only.

4. Results and discussion

4.1. *Maximum and minimum temperatures*

The mean minimum, maximum and the mean temperature observed in the course of the day for air and various soil depths are shown in Fig. 1 which also indicates daily temperature range, at different levels below and above the ground. It is found that the maximum diurnal variation occurs at the ground surface, then decreases with increasing soil depth. The diurnal variation of soil temperature decreases very rapidly with increasing soil depth. The diurnal soil temperature wave penetrates up to 20 cm with a range of about 2°C. At 30 cm depth, the soil temperature curve is practically straight suggesting absence of diurnal features. Above 20 cm depth and at the screen level the large diurnal variations are conspicuous. The largest amplitude for obvious reasons, is observed at the ground level followed by 5 and 10 cm depths. The temperature range at the screen level has an amplitude whose magnitude is almost equal to that at 5 cm depth. There is not much variability seen in the mean temperature from 30 cm soil depth to the ground surface as well as mean temperature at the screen level.

The time lag between occurence of minimum temperature and the time of sunrise is given in Fig. 2(a). The air temperature attains a minimum after about 20 minutes of sunrise while at the ground surface these two coincide. The time of occurrence of minimum soil temperature progressively increases with depth. At 30 cm depth, minimum soil temperature is reached about 8 hours and 30 minutes after sunrise.

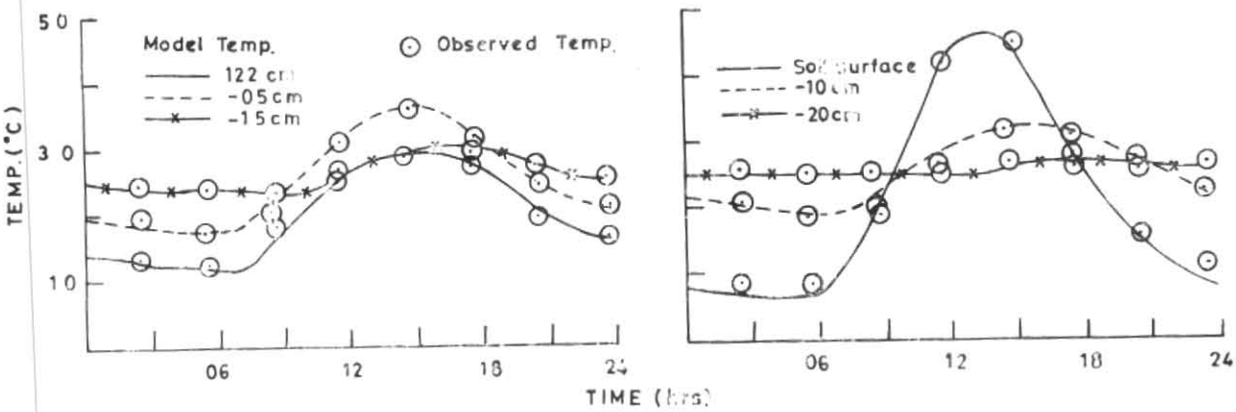


Fig. 4. The model and the observed temperature

TABLE 1

Values of α and β coefficients and temperature error for different layers

Level (cm)	Coefficients		Absolute Mean Error (AME) and Root Mean Square Error (RMSE) of temperature					
			Day hours		Night hours		Days average	
	α	β	AME (°C)	RMSE (°C)	AME (°C)	RMSE (°C)	AME (°C)	RMSE (°C)
122	2.30	3.1	0.60	0.66	0.45	0.53	0.53	0.60
Ground surface	0.95	3.5	1.73	2.23	1.03	1.18	1.37	1.78
—05	2.00	3.2	1.37	1.65	0.37	0.40	0.37	1.20
—10	3.40	2.9	1.35	1.60	0.33	0.70	0.84	1.16
—15	4.70	2.0	0.80	0.99	0.45	0.46	0.63	0.77
—20	8.50	1.5	0.43	0.19	0.30	0.23	0.36	0.15

The occurrence of maximum temperature with respect to the time of sunset is shown in Fig. 2 (b). It is observed from the figure that whereas air temperature attains its peak about 3 hours and 45 minutes before the sunset, the interval progressively diminishes with depth from 5 hrs before sunset at the ground surface to 6 hours and 30 minutes after sunset at 30 cm depth. At 15 cm depth, maximum is reached about 1 hour and 30 minutes before sunset while at 20 cm depth 3 hours and 30 minutes after sunset the peak temperature is realised. The rate of downward progression of temperature wave appears 25 min/cm for maximum and about 15 min/cm for minimum temperature.

In the study, parameters α and β have been estimated from the observed data. The values of these coefficients, for different soil depths and air temperature, are given in Table 1. Variations in α and β with depth (d) have been shown in Fig. 3. Both these parameters seem to be related with depth exponentially and have been represented in this study by the following equations :

$$\alpha = 0.95/\exp\,(-0.23\ d^{\,0.75}) \quad (3)$$

$$\beta = 3.5\ \exp\,(-0.005\ d^{\,1.72}) \quad (4)$$

The lag coefficient α for the maximum temperature generally increases from about 1-hour near the ground surface to 12 hours at 30 cm depth. The night time temperature coefficient β is found to decrease generally with depth from 3 hours 30 minutes at the ground surface to 1 hour 30 minutes at 20 cm depth. This suggests that at depths in the immediate vicinity of the ground surface the rate of fall of temperature is conspicuously high. Beyond 20 cm depth, the thermal regime appears largely independent of the occurrence of minimum/maximum temperatures since the amplitude at these levels is inconspicuous (Chowdhury *et al.* 1991).

The values of α and β were subsequently used to compute the temperatures for day and night hours. The model and the observed values for various levels are shown in Fig. 4. A remarkably close fit between the two sets of values can be easily seen for nearly all cases. At the surface, however, a minor departure between the computed and recorded values are observed. Detailed analysis of the data showed that on an average the temperature at the ground surface dropped between 1430 IST and sunset at the rate of more than 6°C/hr. The maximum temperature, as is known, occurs around 1430 IST.

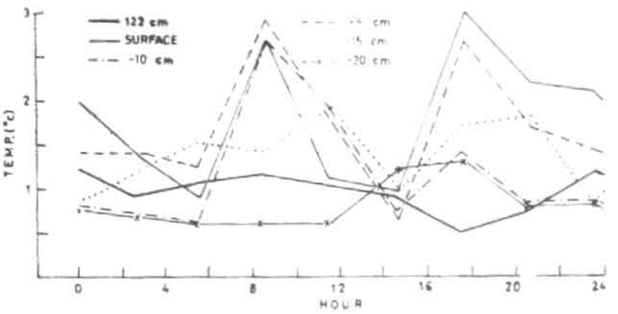


Fig. 5. Root mean squared error (°C) for the air and soil temperatures as a function of time of day

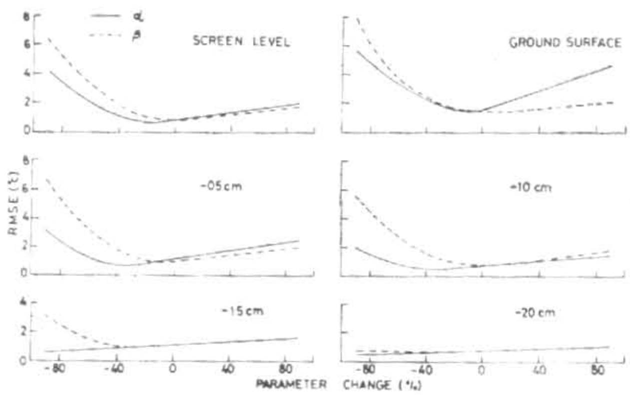


Fig. 6. Changes in the root mean squared error for different layers that result from changing α and β values used in the model

Subsequently, the outgoing heat flux overshadows the incoming solar radiation. The difference between the two gets accentuated because of the thermal properties of the soil. Some heat also gets transferred down wards from the warmer soil surface between 1430 IST and sunset, when the sun's elevation is low. This results in sharp fall of ground surface temperature between the two epochs. The model could not accommodate such rapid decrease in the temperature, resulting in some deviations of the model values from those observed at the soil surface.

4.2. *Error analysis*

The Absolute Mean Error (AME) and Root Mean Square Error (RMSE) for temperatures at various depths are given in Table 1 to see how far the model values compare with the observed data. The absolute errors of day time temperature are quite low. The RMSE for day time temperature does not exceed 2°C except at the ground surface. The high RMSE values at surface could also be due to the large difference between model and observed temperatures during 1430 IST and the time of sunset, as noticed in the previous paragraph. The error terms for the night time temperature including those for ground surface, were also very low. This confirms our earlier explanation that it is the large temperature fall between the day time maximum temperature and sunset epochs which contributes to large errors between the model and those recorded.

The RMSE calculated for different hours is shown in Fig. 5. The error term appears nearly homogeneous at the screen level. However, it tends to be largest during 0900 and 1800 IST. This pattern is most pronounced at the soil surface and up to 10 cm depths. At these levels RMSE is nearly 1°C in early morning hours (0300-0600 IST) but increases to nearly 3°C at 0900 IST, falls back to nearly 1°C during noon hours (1200 - 1500 IST) and rises to 3°C at 1800 IST (around sunset time). At other layers the error term is less than 1°C.

4.3. *Sensitivity analysis*

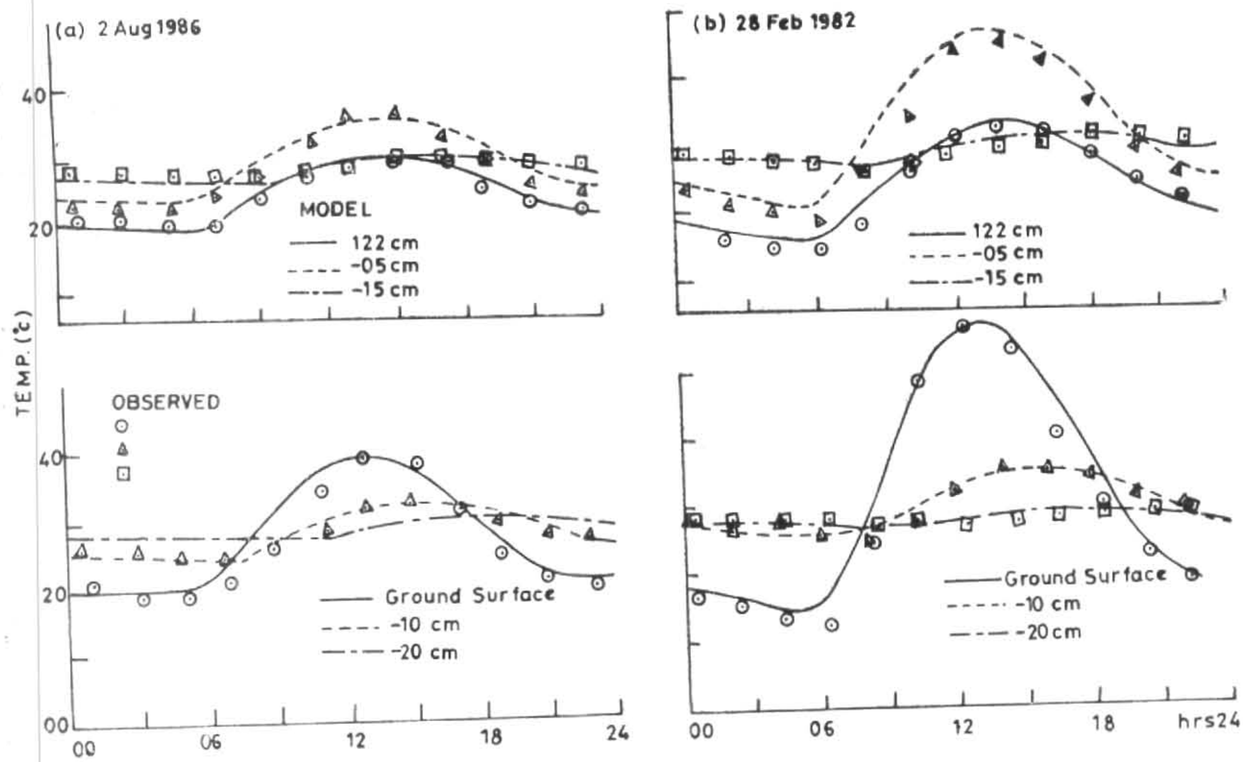
A sensitivity analysis was performed by varying the constants α and β by $\pm$ 90% about the model values. The results are depicted for all levels in Fig. 6. It is seen that, except at ground surface, the positive changes have relatively little impact on RMSE. At the ground surface the RMSE increases with the increase in the values of the constants. Change of —30% from mean do not appear to have much impact on RMSE and on negative side RMSE observed to be more sensitive to changes in β than that in α.

4.4. *Model validation*

It is clear that the model gives highly consistent values in estimating temperatures at any hour except during 0900 and 1800 IST at ground surface and its immediate vicinity.

The model was tested with an independent data for two sets of continuous days, one during monsoon (2-6 August, 1986) when the sky is mostly overcast and winter (24-28 February 1982) when sky is clear and wind is generally light. The simulated and observed values for two typical days are shown in Figs. 7 (a & b) respectively.

By and large, results for simulated air and soil temperature layers compare favourably with actual observations. The absolute mean and RMS errors for these days are given in Table 2. The error (absolute mean and root mean square) are, for any level, found less in monsoon period compared to winter. During rainy season at ground surface and lower depths, the temperature ranges are low due to presence of soil moisture and hence the model values give estimates between 1° and 2°C of the observed values. In winter higher temperature range perhaps, gives rise to large difference between estimated and observed values.



Figs. 7 (a & b). Observed *versus* simulated temperature (a) 2 Aug 1986 and (b) 28 Feb 1982

TABLE 2 (a & b)

Absolute Mean Error (AME) and Root Mean Square Error (RMSE) for independent data

Date	Screen level		Ground surface		—05 cm		—10 cm		—15 cm		—20 cm	
	AME	RMSE	AME	RMSE	AME	RMSE	AME	RMSE	AME	RMSE	AME	RMSE
(a) Non-monsoon period (clear sky)												
February												
24	1.46	1.83	2.52	2.88	1.63	2.21	0.95	1.13	0.76	0.94	0.38	0.57
25	1.48	1.80	2.05	3.13	2.19	2.88	0.93	1.08	0.75	0.89	0.65	0.77
26	1.21	1.43	2.21	1.73	0.79	1.44	0.75	0.89	0.75	0.87	0.41	0.58
27	1.12	1.41	2.06	2.68	1.95	2.72	0.83	1.03	0.63	0.76	0.70	0.83
28	1.04	1.32	1.68	2.87	2.02	2.53	1.37	1.85	1.39	1.68	0.63	0.73
Mean	1.26	1.56	2.10	2.66	1.72	2.36	0.97	1.20	0.86	1.03	0.55	0.70
(b) Monsoon period (overcast sky)												
August												
2	0.66	0.88	1.86	2.66	1.29	1.64	0.67	1.01	0.33	0.49	0.35	0.41
3	0.65	0.86	1.22	1.70	1.00	1.23	0.45	0.49	0.36	0.43	0.37	0.40
4	0.75	0.89	1.37	1.83	0.90	1.09	0.55	0.81	0.16	0.20	0.24	0.28
5	1.17	1.47	2.19	2.96	1.45	1.91	0.99	1.31	0.22	0.27	0.22	0.27
6	0.85	1.11	1.48	1.81	1.53	1.72	1.19	1.38	0.42	0.49	0.16	0.19
Mean	0.82	1.03	1.62	2.19	1.23	1.52	0.77	1.00	0.30	0.38	0.27	0.31

Another striking feature is that in both sets, the error terms progressively decrease with soil depth.

The error (AME and RMSE) are large at surface, 5 cm and 10 cm depths. This, perhaps, could be due to large temperature range found at the surface. The thermal wave, according to Chowdhury *et al.* (1991) penetrates deep in soil and its effect is more in layers just below the soil surface. This explains large errors observed in these levels.

4.5. *Model comparison*

In the study, an attempt was also made to estimate air and soil temperatures at various depths using Fourier technique and orthogonal functions. The temperatures were estimated for all 8 observations at 0230, 0530, 0830, 1130, 1430, 1730, 2030 and 2330 IST. In order to find how best the estimated temperatures by these methods compare with actual values, the RMSE was calculated. The error term was largest at ground surface level in the orthogonal method and the screen level in Fourier technique and in each case gradually decreased from its peak downwards.

The sine-exponential model when compared with the two models shows that, for each level, RMSE was lowest in Fourier analysis and maximum in orthogonal functions. At 5 cm depth, for instance, the error was 1.8°C by sine-exponential model, 1.9°C by orthogonal function and 1.3°C by Fourier technique. Other depths also showed similar trend. Though Fourier technique appears, little impressive, the superiority of the sine-exponential model lies in the fact that it needs just 2 parameters against 8 needed by the other two methods.

5. Conclusion

The study has the application of sine-exponential model to estimate day and night time air and soil temperatures. The error terms are found low (*i.e.*, less than 2°C) and homogeneous for all cases. However, the error tends to be largest for the ground surface during the day hours with RMSE of 2.2°C, a large part of this was contributed by the afternoon heating and subsequent rapid cooling.

The model furnishes persistently accurate temperature estimates though it substantially over estimates during afternoon hours at the ground surface. As the model considers, besides other parameters, the length of day and night, it could be successfully applied to any season.

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