RESEARCH ARTICLE

The Estimation of Daily Mean Soil Temperature at Different Depths in Three Agroecological Regions of Sri Lanka

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ABSTRACT

Soil temperature is an important climatic variable in regulating ecosystem process, yet it is difficult and costly to measure daily. Several mathematical models are available to estimate soil temperature; however, most are with complicated independent variables. In this research, site specific parsimonious models were developed to estimate daily mean soil temperature in deeper depths (i.e.>10 cm) using air temperature, soil temperature at 5 cm depth and day of the year as independent variables. Different models were developed for four Coconut growing sites and results showed that 5 cm depth soil temperature along with day of the year estimate the soil temperature at deeper depths with high accuracy. Further, models with air temperature and day of the year estimate the soil temperature at 5 and 10 cm depths satisfactorily. These models can be used to estimate the daily mean soil temperature simply and cost effectively and it also allows the reconstruction of missing soil temperature values.

Key words: Soil temperature, Agroecological regions, Parsimonious models, Coconut

INTRODUCTION

Soil temperature is an important variable among climatic variables, which significantly affects below ground biological processes (Shanon *et al*, 2000). Soil respiration is one of the most influential phenomenons to soil temperature variations (Boone *et al*, 1998). In addition, microbial decomposition of organic matter, mineralization processes and soil properties such as pH, ion concentrations also about the below ground processes. However, the availability of data on soil temperature is

depend on soil temperature changes (Tomlinson, 1993).

Burton and the team (1998) claimed that soil temperature exponentially relates with fine root respiration (Burton *et al*, 1998). Shanon *et al*, (2000) revealed that monthly or annual time steps based models could not accurately predict the dynamic changes in above processes and models based on shorter time steps are important to make inferences about the below ground processes. However, not abundant as air temperature data to make such inferences or to develop true

relationships with other important soil biological processes. Further, measuring soil temperature at different depths is costly and laborious. Even in the weather stations of Sri Lanka, the availability of soil temperature data is rare. Even if it is measured; readings are confined to shallow soil depths i.e. 5 – 10 cm depths. However, soil temperatures at deeper depths are required to understand the processes such as root growth, carbon dioxide emission and fertilizer dynamics, when considering perennial crops such as coconut. Daily measurement of soil temperature at deeper depths is prohibitively time consuming. Occasional equipment failure and bad weather (i.e. heavy rains) may interrupt data collection leading to missing temperature readings. Therefore, the estimation of soil temperature using a statistical model has great importance in meteorological studies.

There are two different approaches to estimate the soil temperature (Kang *et al*, 2000). First method is based on the soil heat flow and energy balance and several models have been developed (Thunholm, 1990) using this method. The second method is based on empirical regression models with environmental parameters such as air temperature, rainfall, evaporation etc. (Shanon, *et al*, 2000; Zheng *et al*, 1993). The first method gives accurate predictions compared to the second method (Kang *et al*, 2000), but it demands input variables such as soil thermal capacity and soil thermal conductivity which are of limited availability.

Numbers of examples are available in the literature for use of regression based soil temperature prediction models (Parton, 1984; Toy *et al*, 1978). However, the accuracy of the estimates of these models depends on the key regression coefficients which are site specific in many cases (Kang *et al*, 2000) because soil temperature is affected by the soil water content, soil colour and soil surface conditions etc (www.wtman.edn/~crobinson/soiltemp/).

The objective of this paper was to develop site specific models to estimate daily soil temperature at different depths using daily air temperature and other variables such as daily rainfall and daily pan evaporation. Our attempt was to develop precise parsimonious models to predict soil temperature with largely available meteorological data.

MATERIALS AND METHODS

Research sites

Three sub research stations of Coconut Research Institute of Sri Lanka (CRISL) namely, Ambakele, Bandirippuwa and Maduruoya were selected for the study. A brief description of each site is shown in the Table 1.

Data collection

Daily soil and air temperatures, daily rainfall and pan evaporation recorded at above sites from year 1995 to 2005 (except for Maduruoya site where data were used from 1996 to 2005) were used for this study. In these sites, soil temperatures were measured twice a day (08.30 and 15.30 hrs) at 5, 10, 20, 30, 60 and 120 cm depths using mercury soil thermometers.

Table 1. Location and site characteristics of the three sited used in this study. Mean temperatures and rainfall are based on the measurements made from year 2005 to 2010.

	Ambakelle	Bandirippuwa	Maduruoya
Latitude	7^0 58' N	7^0 33' N	7° 52' N
Longitude	79^0 78' E	79^0 88' E	81° 31' E
Agro ecological region	$IL1_b$	$IL1_a$	$DL1_c$
Annual mean air temperature (˚C)	28.9 (0.947)	28.2 (0.762)	30.9 (1.882)
Annual mean soil temperature (˚C) (at 5 cm depth)	31.5 (1.697)	30.3 (1.308)	31.5 (2.367)
75% expectancy of annual rainfall (mm)	>1100	>1400	>900
Soil Type[†]	Imperfectly drained , deep, dark yellowish brown to very pale brown, coarse loamy and coarse sandy loams over gravelly clayey soils	Moderately well drained to imperfectly drained, deep, light graish brown to yellowish brown, coarse loam soils	Moderately well drained, dark brown, sandy clay loamy soils

[†]Source - Somasiri *et al*, 1994; Note: Values in parenthesis are standard deviations.

The average of two morning and afternoon values were considered as the daily mean soil temperature. Daily air temperature was measured in a Stevenson screen about 2 m above the ground level using mercury thermometers in all three locations at the same time. The average of the two records was considered as the daily mean air temperature. The missing data for above time period were not considered for the analysis as this number was negligible.

Statistical modeling

Air and soil temperature relationship

Scatter plots were used to see the underline relationship between the two variables. Various indices of air temperature (such as daily mean, daily mean lag 1, running means of 3, 5 and 10 days), daily rainfall and daily pan evaporation were used as explanatory variables to estimate the soil temperature at different depths.

Relationship between soil temperatures at different depths

Different statistical models were tested to estimate the soil temperature at 10, 20, 30, 60 and 120 cm as a function of soil temperature of 5 cm depth. As with the previous case, different forms of the 5 cm soil temperature i.e. daily mean, mean of the previous day, 3, 5, 10 days running mean were used as explanatory variables along with daily rainfall and daily pan evaporation.

Since the soil temperature varies with the day of the year (DOY), it was also considered as an independent variable in both analyses. The summary of the models considered in the study are as below.

$$Y_{ij} = \beta_0 + \beta_1 X_T + \varepsilon \qquad \text{Eq 01}$$

$$Y_{ij} = \beta_0 + \beta_1 X_T + \beta_2 (DOY) + \varepsilon \qquad \text{Eq 02}$$

$$Y_{ij} = \beta_0 + \beta_1 X_T + \beta_2 (DOY) \\ + \beta_3 (RF) + \varepsilon \qquad \text{Eq 03}$$

$$Y_{ij} = \beta_0 + \beta_1 X_T + \beta_2 (DOY) + \\ \beta_3 (RF) + \beta_4 (EV) + \varepsilon \qquad \text{Eq 04}$$

Where, Y_{ij} = Soil temperature at i^{th} depth (i = 10, 20, 30, 60 and 120 cm) in j^{th} day of a given year (j = 1......365); X_T = daily mean air temperature/ 5 cm soil temperature; *DOY* = day of the year;
RF = total rainfall in j^{th} day in mm; *EV* = pan evaporation in j^{th} day in mm

Model evaluation

Each of the fitted models was compared to select the best fitted model for a given site. Adjusted coefficients of determination (R^2_{adj}) and mean square error (MSE) of the model were used to evaluate the performance of the models. Along with that, minimization of Akaike information criterion (corrected) (AIC_c) and Shewaz's Bayesian information criterion (BIC) (Rawlings *et al*, 1998) were used to select the best fitted models. Residual plots of each fitted models were also used as a model evaluation criterion. The estimation of model parameters and model evaluation was done using the ordinary least square method (OLS) in SYSTAT® statistical software, version 12 (SYSTAT Inc 2, 2007). Selected models were used to estimate the daily mean soil temperature at different depths in year 2006 in all sites. The difference between the observed and estimated soil temperature was used to evaluate the performance of the model.

RESULTS

Variation of daily mean soil temperature at different depths in three sites

Figure 1 shows the variation of daily mean soil temperature at different depths against the day of the year in three study sites. The Figures, 1(a) and 1(b) reveal that the soil temperature in Bandirippuwa and Ambakele follow a bi-peaked pattern with clear peaks around 90-100 and 250-260 DOYs. This pattern is common for all depths but the peak temperature and the apex vary with the soil depth. In the latter peak (around 250 DOY), soil temperature in Ambakelle is high compared to the Bandirippuwa site. There is no bi-peaked pattern in Maduruoya site, but three clear phases can be identified. In phase I (from 1 to 100 DOYs), soil temperature shows an increasing trend and looks like a flatue with random ups and downs in the II phase (from 100 to 275 DOYs) and decreases thereafter during the phase III. There are three to four minor peaks that can be identified during the second phase up to 30 cm depth. These minor peaks are not clear at 120 cm depth; however, the pattern of change is more or less similar to the other depths. The daily mean soil temperature decreases as soil depth increases in all sites. However, this is not common for any day of the year where soil temperature at lower depths go beyond that of the upper soil layers especially during November to January period where soil temperature shows lower values (see Figure 1).

Temperature values given are the means of the daily temperatures over the study period (1995 to 2005 in Ambakelle & Bandirippuwa and 1996 to 2005 in Maduruoya). Note the different vertical scales in different graphs.
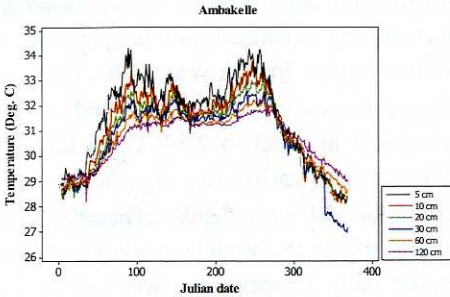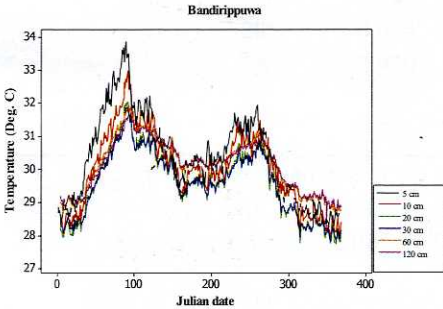

Figure 1 (a)
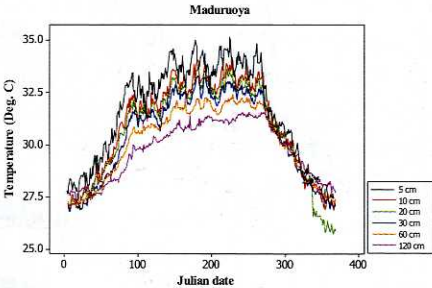

Figure 1 (b)

Figure 1 (c)

Figure 1. Variation of daily mean soil temperature at different depths with the day of the year in (a) Ambakelle, (b) Bandirippuwa and (c) Maduruoya sites.

Variation of daily mean air temperature in three sites

The distribution of daily mean air temperature within year is shown in Figure 2 for the three sites. The distribution is similar to the soil temperature where the bi-peaked distribution is common for Ambakelle and Bandirippuwa sites. In both sites, the air temperature rapidly increases up to 100 DOY and declines slowly thereafter until 200 DOY. After that, it slowly builds up to the second peak around 270-275 DOYs and then declines. In Maduruoya site, it shows an exponential increase up to 100 DOY, thereby slight drop followed by an increase of air temperature up to 170 DOY. After that it follows an irregular plateau and starts to decline from about 275 DOY.
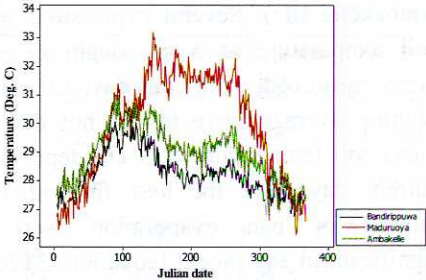
Figure 2

Figure 2. Variation of daily mean air temperature with the day of year in three sites. Note: Temperature values given are the means of the daily temperatures over the study period (1995 to 2005 in Ambakelle & Bandirippuwa and 1996 to 2005 in Maduruoya).

Model development and evaluation

Relationship between soil temperatures at different depths with the temperature of 5 cm soil depth

Table 2 summarizes the ordinary least square (OLS) estimates of the parameters of best fitted models, MSEs and diagnostic measures used for model evaluation. A strong relationship between soil temperatures at different depths and at 5 cm soil temperature was found and all the model parameters were statistically significant (P < 0.05). The best fitted model for most of the cases was linear and of the for $Y_{ij} = \beta_0 + \beta_1 X_{ij} + \beta_2 (DOY) + \varepsilon$ and the model $Y_{ij} = \beta_0 + \beta_1 X_{ij} + \varepsilon$ gave the best fit for two situations (for 20 cm depth at Maduruoya site and 30 cm depth at Ambakelle site). Several expressions of the soil temperature at 5 cm depth i.e. daily mean, mean of the previous day, 3, 5, 10 day running average were tested, but the daily mean soil temperature at 5 cm depth of the current day gave the best fit. Indices of rainfall or pan evaporation were not significant in any model [equation (3) & (4)] and didn't make substantial improvement of the model.

The model parameters vary consistently with soil depth. However, parameter of the DOY was more or less similar in each site for different soil depths. Since the value of the parameter is small (< 0.005) contribution of the DOY to the soil temperature is low compared to the temperature at 5 cm depth but, inclusion of DOY as an input variable had a great impact on the performance of the models where increase in R^2_{adj} and reduction

in both AIC_c and BIC was observed In Ambakelle site, all the models show high R^2_{adj} values (> 86%). The mean square error (MSE) of the models ranged from 0.17 to 0.32 which is a narrow range. MSE increases with the soil depth. Figure 03(a) shows the observed and predicted soil temperatures at different depths for the year 2006. The error $(T_{observed} - T_{predicted})$ of the best fitted models varies with in -1.82 to 2.39 ˚C. In this site, DOY was not statistically significant in the model for 30 cm depth. Therefore, the equation 01(i.e. the model containing only the average daily temperature) was selected as the best fitted model for 30 cm depth.

Table 2. Parameters and diagnostic measures of selected models to estimate the mean soil temperature at different depths in Ambakelle, Bandirippuwa and Maduruoya sites.

Site	Soil depth (cm)	β_0	β_1	β_2	R^2_{Adj}	AIC_c	BIC	MSE
	10	2.431	0.906	0.001	0.99	-253.06	-237.57	0.17
	20	4.551	0.827	0.001	0.97	-19.51	-19.39	0.23
Ambakelle	30	4.149	0.840	NA	0.92	423.03	434.66	0.43
	60	10.429	0.629	0.002	0.93	138.16	153.65	0.29
	120	14.627	0.491	0.003	0.87	213.55	228.99	0.32
	10	2.812	0.890	0.001	0.97	-195.57	-180.08	0.184
	20	5.412	0.790	0.001	0.95	-24.74	-9.25	0.232
Bandirippuwa	30	6.904	0.742	0.001	0.94	-3.80	11.685	0.239
	60	11.009	0.623	0.001	0.86	153.43	168.92	0.296
	120	12.794	0.564	0.001	0.83	200.08	215.56	0.316
	10	0.981	0.941	0.001	0.99	-59.74	-44.25	0.221
	20	0.624	0.949	NA	0.97	369.38	408.01	0.414
Maduruoya	30	2.970	0.856	0.002	0.98	166.95	182.44	0.302
	60	7.069	0.712	0.003	0.97	220.15	235.63	0.325
	120	12.820	0.511	0.004	0.92	358.92	374.42	0.393

Note: NA; parameter not available in the model. All the parameters were statistically significant (P<0.05). AIC_c = Akaike information criterian (corrected); BIC = Shewaz's Bayesian information criterion; MSE = Mean square error
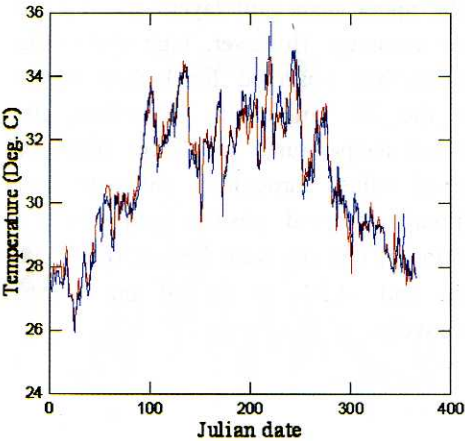

Figure 3 (a) – I

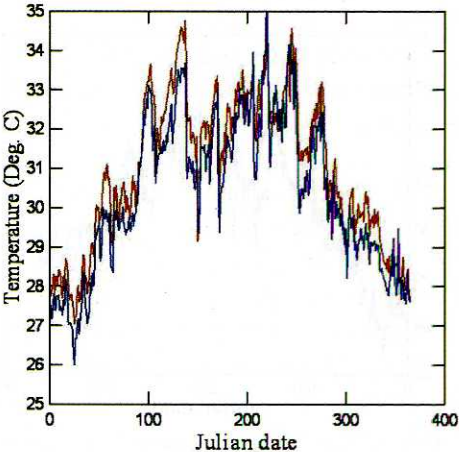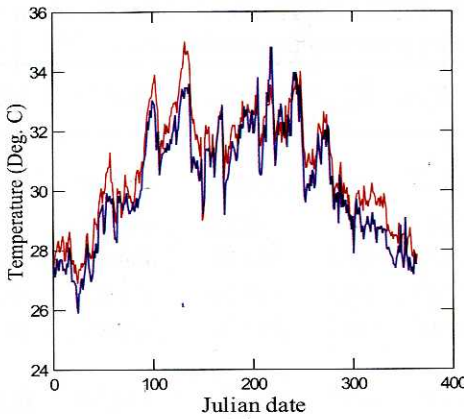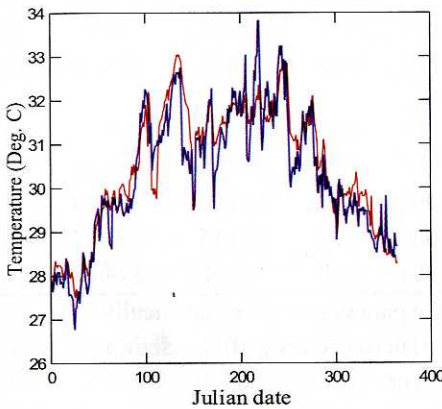*Figure 3 (a) – II*

Figure 3 (a) – III
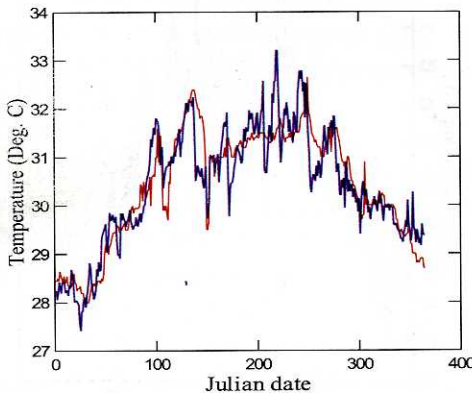

Figure 3 (a) – IV

Figure 3 (a) – V

Figure 3 (a). Observed and estimated daily mean soil temperatures at I = 10 cm, II = 20 cm, III = 30 cm, IV = 60 cm, V = 120 cm soil depths from January 1 to December 31, 2006 for Ambakelle   site. In each graph, blue (dotted) line represents the estimated daily mean soil temperature, and the red (thick) line representing the observed daily mean soil temperatures.

The best fitted models for each soil depth at Bandirippuwa site were according to the equation 02 and all showed high R^2_{adj} values

(> 83%). However, the R^2_{adj} of 60 and 120 cm depths were lower compared to the models of other depths (Table 02). In this site, parameters of the DOY were similar for all depths and are statistically significant (P < 0.001). MSE of the fitted models were in a narrow range from 0.184 to 0.316. As in Ambakelle site, MSE increased with the soil depth. The observed and predicted soil temperatures at each depth for the year 2006 are shown in the Figure 03 (b). The estimates for the upper three soil layers showed the higher accuracy. However, high systematic deviation was observed for bottom layers from the 30 cm depth. Therefore, the predicted temperatures are lower than the observed values throughout the year. The maximum observed positive and negative deviation of this site were 3.86 ˚C (in 60 cm depth) and -4.24 ˚C (in 10 cm depth) respectively.
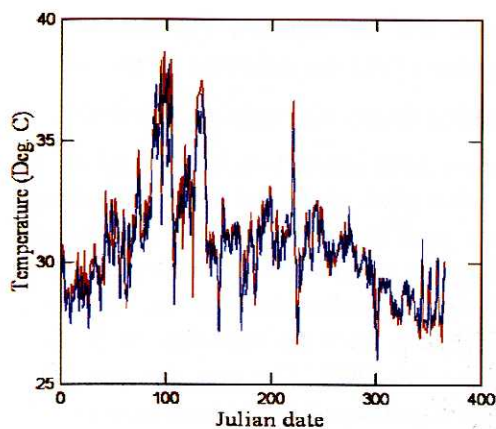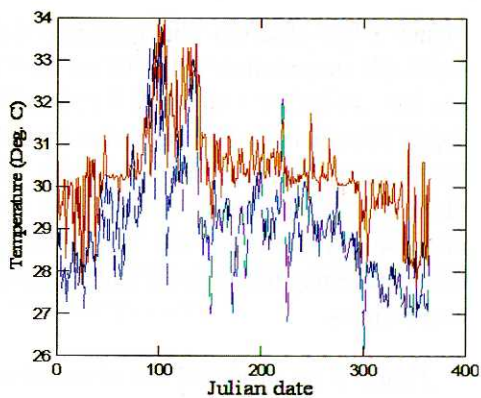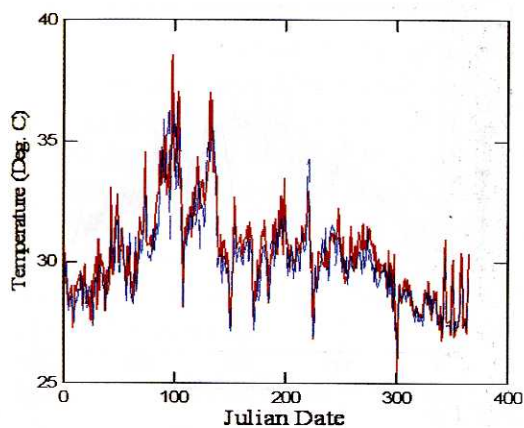
Figure 3 (b) – I

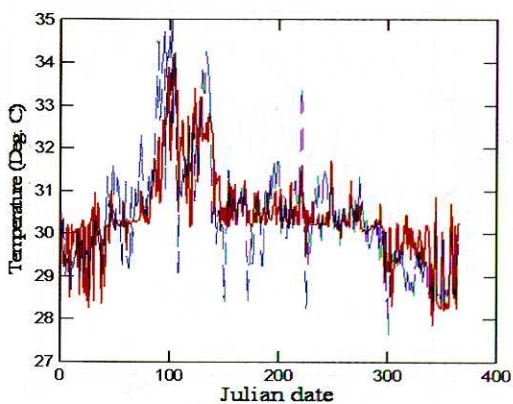*Figure 3 (b) – IV*

Figure 3 (b) – II
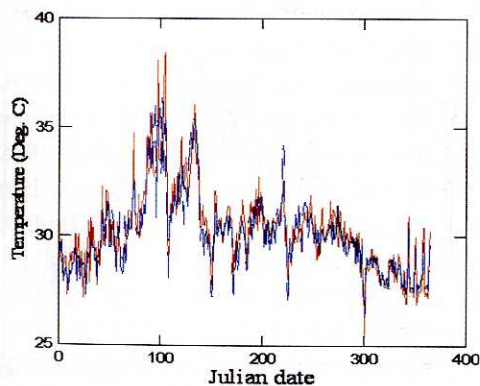

Figure 3 (b) – V
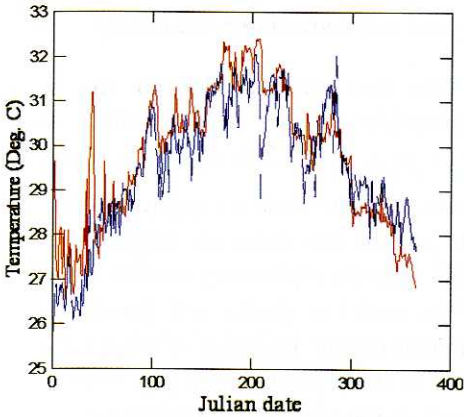

Figure 3 (b) – III

Figure 3 (c) – V

Figure 3 (c) observed and estimated daily mean soil temperatures at I = 10 cm, II = 20 cm, III = 30 cm, IV = 60 cm, V = 120 cm soil depths from January 1 to December 31, 2006 for Maduruoya site. In each graph, blue (dotted) line represents the estimated daily mean soil temperature, and the red (thick) line representing the observed daily mean soil temperatures.

Applicability of selected models in other sites

Best fitted models for Ambakelle site were used to simulate the soil temperature at respective depths in Rathmalagara (Lat. 7° 33', Lon. 79° 53') for year 2005. Figure 3(d) displays the observed and predicted soil temperatures at Rathmalagara site in year 2005. Selected models showed good fits for each depth in both sites, except for 120 cm in Rathmalagara site. It evidenced the applicability of the selected models in different agroecological regions within the same agroclimatic zone. However, this could be further validated using data from different locations over several years.

Figure 3d. Observed and estimated daily mean soil temperatures at I = 10 cm, II = 20cm, III = 30 cm, IV = 60 cm, V = 120 cm soil depths from January 1 to December 31, 2005 for Rathmalagara site. In each graph, blue (dotted) line represents the estimated daily mean soil temperature, and the red (thick) line representing the observed daily mean soil temperatures.
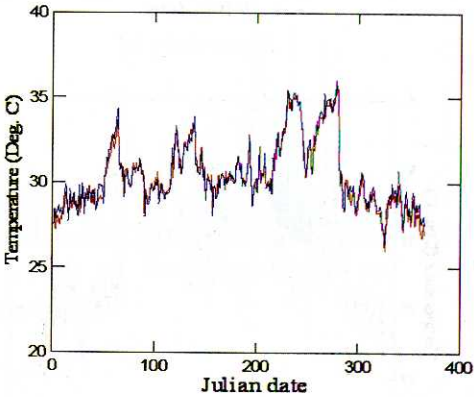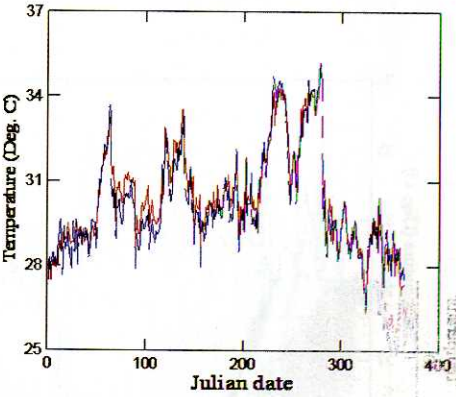

Figure 3 (d) – I

Figure 3 (d) – II

Figure 3 (b) observed and estimated daily mean soil temperatures at I = 10 cm, II = 20 cm, III = 30 cm, IV = 60 cm, V = 120 cm soil depths from January 1 to December 31, 2006 for Bandirippuwa site. In each graph, blue (dotted) line represents the estimated daily mean soil temperature, and the red (thick) line representing the observed daily mean soil temperatures.

Figure 3 (c) displayed the observed and predicted soil temperatures at different depths in Maduruoya site for year 2006. In this site, the best fitted model for the 20 cm

depth was the equation (1) and it was equation (2) for the rest of the depths. All the selected models have high R^2_{adj} (> 0.90) and narrow MSE ranged from 0.221 to 0.414. As in other sites, models of the top soil layers gave good fit for the observed data in year 2006. The model of the 120 cm depth showed substantial underestimation of the soil temperature from the beginning of the year up to 100 DOY. However the maximum positive and negative deviations were 4.09 °C (at 120 cm depth) and -3.04 °C (at 10 cm depth).
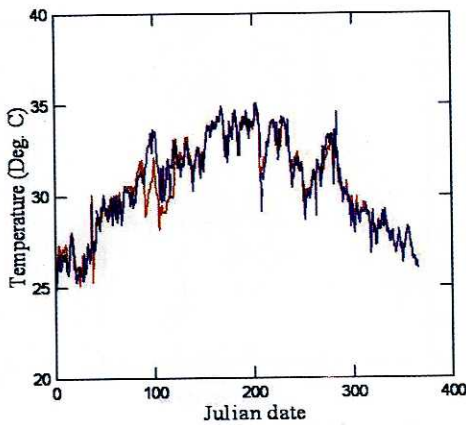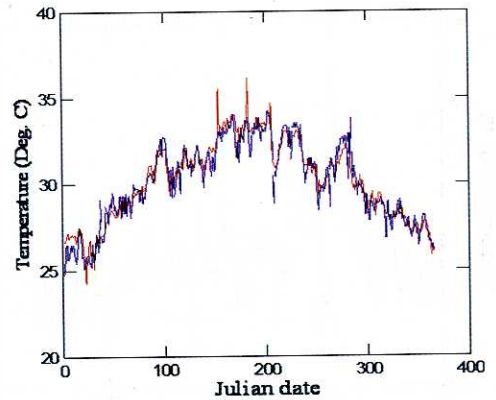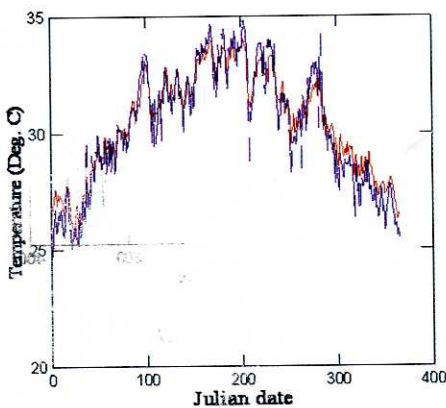

Figure 3 (c) – I

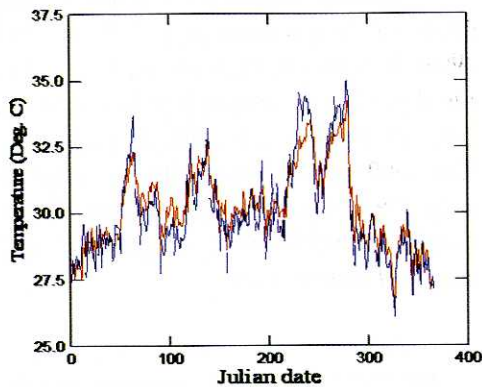*Figure 3 (c) – III*

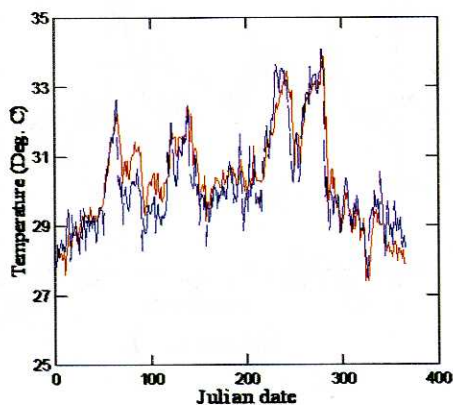*Figure 3 (c) – II*
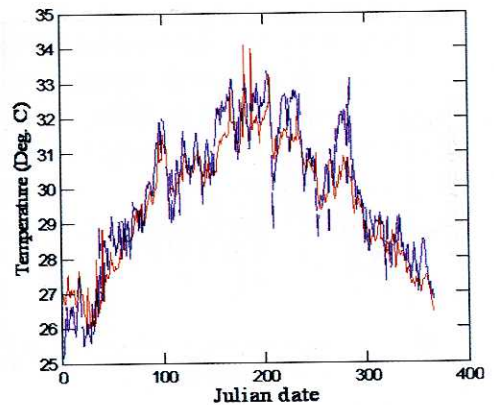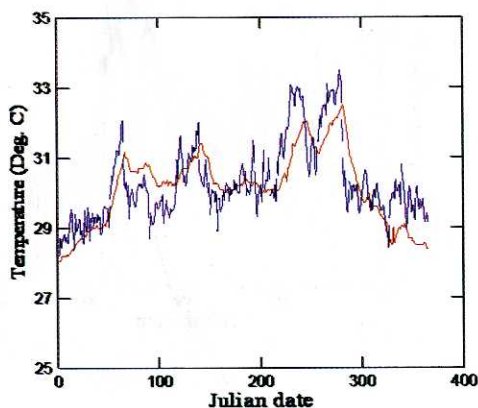

Figure 3 (c) – IV

Figure 3(d) - III

Figure 3(d) - IV

Air and soil temperature relationship

The best fitted model for the above relationship was of the form, $Y_{ij} = \beta_0 + \beta_1 X_{ij} + \beta_2 (DOY) + \varepsilon$ and the parameters estimated are given in Table 03. The current day mean air temperature and DOY were the explanatory variables included in the model to predict soil temperature at different depths. Inclusion of other variables such as daily rainfall and pan evaporation didn't improve the model performances.

The selected models to predict the soil temperature of the upper soil layers (5 and 10 cm depths) showed higher R^2_{adj} values (Table 3). Low R^2_{adj} (< 0.50) and high MSE for the predictions were observed at higher soil depths in Bandirippuwa and Ambakele but not in Maduruoya. Therefore, models were selected only for 5 and 10 cm depths in all three sites.

Figure 3 (d) – V
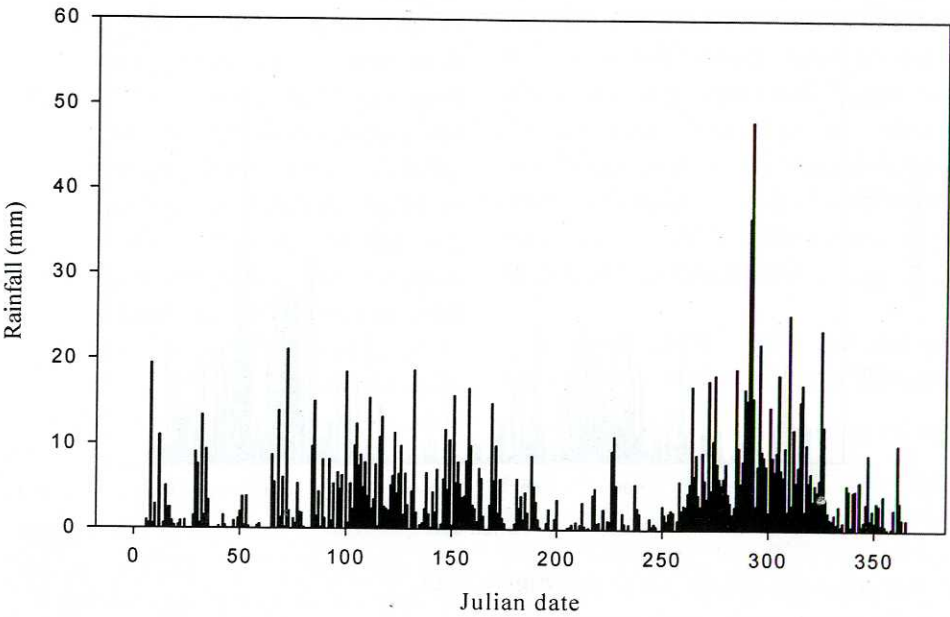
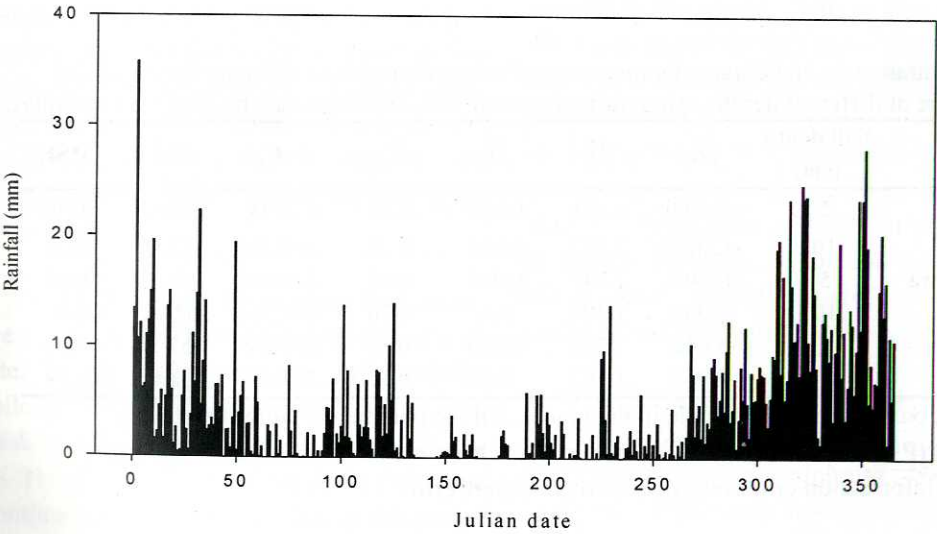**Bandirippuwa**

Figure 4 (a)
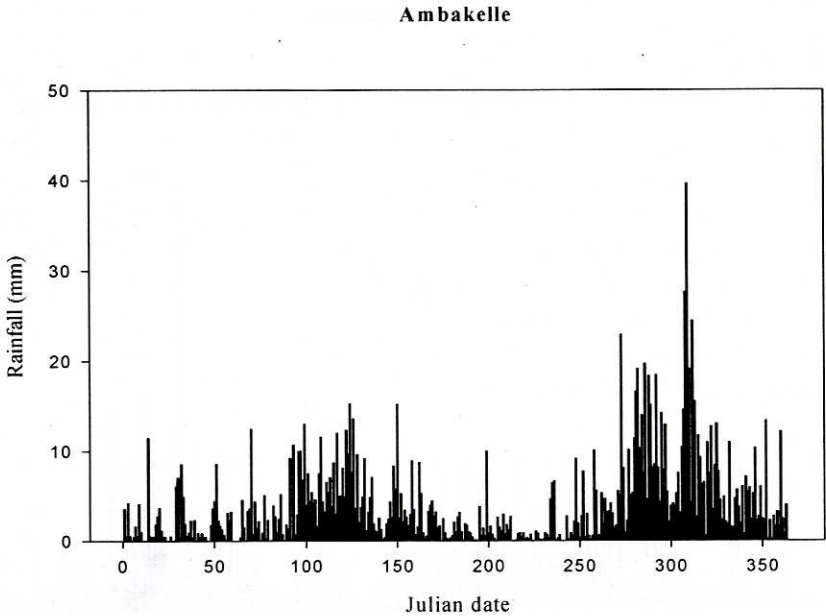
Maduruoya

Figure 4 (b)

Ambakelle

Figure 4 (c)

Figure 4. Distribution of daily rainfall in (a) Bandirippuwa, (b) Maduruoya and (c) Ambakelle sites. Note that daily means are the average of daily rainfall measurements over the study period (i.e. 1995 – 2005 in Ambakelle and Bandirippuwa; 1996 – 2006 in Maduruoya.)

Table 3. Parameters and diagnostic measures of selected models to estimate the mean soil temperature at different depths using air temperature and Julian date as the predictor variables.

Site	Soil depth (cm)	β_0	β_1	β_2	R^2_{Adj}	AIC_c	BIC	MSE
Ambakelle	5	-16.699	1.651	0.002	0.78	870.98	886.47	0.792
	10	-12.899	1.503	0.003	0.78	808.16	823.65	0.73
Bandirippuwa	5	-10.495	1.345	0.003	0.82	440.68	456.16	0.44
	10	-6.980	1.309	NA	0.76	617.13	623.5	0.56
Maduruoya	5	-5.042	1.356	-0.001	0.95	551 .67	567.15	0.51
	10	-0.952	1.162	NA	0.95	523.17	538.65	0.49

Note: NA; parameter not available in the model. All the parameters were statistically significant (P<0.05). AIC_c = Akaike information criterian (corrected); BIC = Shewaz's Bayesian information criterion; MSE = Mean square error

DISCUSSION

The primary objective of this study was to develop site specific statistical models to estimate the daily mean soil temperature at different soil depths using easily measured weather parameters. The results emphasized that, the higher proportion of the variability of soil temperature at different depths is explained by the variability of the soil temperature at 5 cm rather than the daily mean air temperature. Studies conducted elsewhere (Kang *et al*, 2000; Zheng *et al*, 1993; Toy *et al*, 1978) had used the daily mean air temperature along with some other variables to predict the soil temperature in different ecosystems. However, results of this study suggested that 5 cm soil temperature is superior in predicting soil temperature at different depths than the air temperature as those models gave higher R^2_{adj} and lower MSE for the estimates. Plauborg, (2002) pointed out that inclusion of dynamic climate elements such as global radiation, wind speed, or soil water deficit does not lead models to a satisfactory improvement. In this study too, models with daily rainfall, daily pan evaporation as independent variables did not give a satisfactory fit to the observed soil temperature at different depths supporting the above argument.

Both air and soil temperature fluctuations are closely related to the daily rainfall of each site. In Bandirippuwa, the daily rainfall follows a bi-peaked distribution where two peak rainfall periods are prominent (Figure 4). The first peak starts around 90 DOY and continues up to 175 DOY. During this period soil temperature in all depths decline. The latter begins around 250 DOY, reaches a maximum around 300 DOY thereby decline.

Soil temperature in all depths reduces steadily during this period. From 175 to 250 DOYs the daily rainfall is at its minimum and during this period, soil temperature increases. As in Bandirippuwa, variation of daily soil temperature in other sites can be explained by means of daily rainfall. Furthermore, this explanation is valid to the pattern of change in daily air temperature too.

In this study, DOY as independent variable improved the model performances by increasing R^2_{adj} and reducing the standard error of estimates. And it also leads to substantial reduction in both AIC_c and BIC values. Shanon *et al*, (2000) have used Julian date (JD) in his models to predict daily mean soil temperature from daily mean air temperature in four forest stands and claimed that, seasonal trend in over and under estimation of soil temperature can be overcome by including the JD as independent variable in the model. This is also same for this study except for two cases (i.e. in 20 cm depth at Maduruoya site and 30 cm depth at Ambakelle site), as all the best fitted models are having the DOY as independent variable. Specific reasons cannot be given to explain the non significance of DOY in above two situations; however, 5 cm soil temperature alone gave perfect predictions for the observed soil temperatures in those sited.

The model evaluation in this study was performed using the AIC_c and BIC, where the best fitted models minimize these two criterions. These two indices measured the lack of fit and penalized extra parameters to avoid the over fitting (Faraway and Chatfield, 1998). BIC is an efficient index to select

models since it penalizes extra parameters more severely than the AIC. In this study, we used the AIC_c which is the biased corrected AIC (Brockwell and Davis, 1991). This index penalizes extra parameters more efficiently than the AIC thereby, leading to models with minimum input variables.

The mean square error (MSE) of the models developed by the present study is ranged from a minimum of 0.17 (10 cm depth in Ambakelle) to a maximum of 0.43 (30 cm depth in Ambakelle). These values are much lower than the MSEs of the models developed by Toy *et al*, 1978; Parton, 1984 and Shannon *et al*, 2000. Prediction errors of those studies were within ± 1.5 °C for many cases. Selected models in current study predict soil temperature for 2006 satisfactorily, however, an unusual under prediction can be seen in Bandirippuwa site and it could not be explained. These models can be used to predict the soil temperature efficiently at different sites within the same agroecological region where the model was developed. The applicability of these models in different agroclimatic regions have to be further tested. However, site specific models are expected to predict soil temperature at higher accuracy than global models (Plauborg,2002).

CONCLUSIONS

The statistical models developed in this study are able to estimate soil temperatures at different depths with high accuracy. Soil temperature at 5 cm depth and day of the year are the best parameters to explain the variability of soil temperature at different depths satisfactorily. Use of air temperature to estimate soil temperatures at different depth needs further improvements, thereby

only models selected for 5 and 10 cm depths in each site are recommended to estimate soil temperatures. The selected models can be recommended to estimate soil temperatures at given depths in different sites within the same agro climatic zone for which the original models were developed. Recording of soil temperature in these sites can be limited to the 5 cm soil depth, thereby cost and time associated with equipment and data recording can be reduced. These models can be used to replace the missing temperature readings efficiently and it facilitate the long term prediction of soil temperature series and other soil physical, chemical and biological processes. Further researches are needed to validate these models for different agro climatic zones.

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