International Journal of Natural and Applied Sciences, 7(4): 429 – 437, 2011 ISSN: 0794 – 4713
www.tapasinstitute.org/journals/ijonas

ESTIMATION OF BARE SOIL SURFACE TEMPERATURE FROM AIR TEMPERATURE AND SOIL DEPTH TEMPERATURE IN A TROPICAL STATION

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ABSTRACT

Soil surface temperature has critical influence on climate, agricultural and hydrological activities since it serves as a good indicator of the energy budget of the earth's surface. Two empirical models for estimating soil surface temperature from air temperature and soil depth temperature were developed. The coefficient of determination (R^2) of soil surface temperature from the air temperature model ranged from 0.92 - 0.99, while the mean absolute error (MAE) and root mean squared error (RMSE) ranged from 0.5 - 2.48 and 0.77 - 2.63^{0}C respectively. For the soil depth model, the R^2 value ranged from 0.75 - 0.96, MAE ranged between 1.05 and 4.94, while RMSE ranged from 1.28 - 5.25. Both models performed well on days of year (DOYs), under similar prevailing weather conditions during the model training period.

Keyword: Air, Soil, temperature, prevailing weather, energy budget, earth surface

INTRODUCTION

Soil surface temperature finds application in climate, agricultural and hydrological models since it serves as a good indicator of the energy budget of the earth's surface. It actually reveals the outcome of the interaction between the surface, the atmosphere and the surface energy fluxes (Sellers *et al.,* 1988; Camillo, 1991; Running *et al.,* 1994 and Zhang *et al.,* 1995). Various parameterizations of sensible and latent heat fluxes include soil surface temperature. Brook (1976) theoretically estimated the ground heat flux from soil temperature using diffusivity equation. Wang and Bras (1999) estimated ground heat flux from surface soil temperature. Hsieh (2009) also estimated soil heat flux using a single layer soil temperature. Brunel (1989) estimated sensible heat flux from measurements of surface radiative temperature and air temperature at two meters and also estimated actual evaporation.

Measurement of soil surface temperature is not as easy as that of air or soil depth; when using a thermocouple, placement on top soil layer and covering with a light soil layer normally gives different results compared to infrared thermometer measured soil surface temperature (Funch and Tanner, 1968). At the Nigerian Micrometeorological Experiment (Nimex) sites there is only one sensor for soil surface temperature (Infrared Pyrometer KT1582D, Heitronics; accuracy of ±0.5^{0}C).

Soil surface temperature is so important that various methods have been used to estimate it (Bhumaralkar, 1975). Blackadar (1976) introduced a force restore method which was used by Deardorf (1977) to determine soil moisture concentration. Acs *et al.* (1991) developed a soil moisture and temperature prediction model for bare soil surfaces. Mihailovic *et al.* (1999) used five different force restore formulations for soil depth temperature to calculate soil surface temperature. Beik and Saradjian (2003) estimated soil surface temperature from AVHRR thermal infrared data using a split window algorithm. Raj and Fleming (2008) extracted soil surface temperature from Landsat ETM$^+$ data, Mallick *et al.* (2008) also estimated land surface temperature from Land sat-7 ETM+ data.

The objective of this investigation was to develop simple regression models for estimating soil surface temperature from observed air and soil depth temperature in an attempt to determine empirical relations between soil surface temperature and air temperature at 1 m and also between the former and soil temperature at 5 cm depth.

MATERIALS AND METHODS

Study area: The Nimex_1 site is situated at Obafemi Awolowo University, Ile Ife (7^{0}33'N and 4^{0}33'E), Nigeria. It is a level terrain of about 100000 m^2 with an elevation of 288 m above sea level. The climate in Nigeria is tropical with two main seasons namely wet (April to October) and dry (November to March). These seasons are influenced respectively by two air masses; the south-westerlies originating from the Atlantic ocean and north-easterlies that has its source in the Sahara Desert. There is a period of ″little dry season″ or ″August break″ in August during the wet season (Halmiton and Archbold 1945, Balogun 1981). The Nimex-1 was carried out during the transition period between the dry and wet season, just at the end of dry and beginning of wet season. The soil at the site was characterized as loamy sand.

Measurement: The bush on the Nimex -1 site was cleared just before the commencement of the experiment. Soil surface temperature was measured with Infrared Pyrometer KT1582D, soil depth temperatures at depths 5, 10 and 30 cm and air temperature at level 0.9, 4.9 and 10.0 m were measured with PT-100Ω Thermistor Thermocouple and Frakenberger Psychrometer respectively from 19 February to 9 March 2004. Volumetric soil moisture (θ) was measured using Campbell Scientific CS616 water content reflectometer at 0.05 m depth.

Other meteorological parameters like wind speed at 8 levels, wind direction, 3 dimensional wind speed, specific humidity of the air, net radiation and its components and global radiation were also measured. The details of the sensors used are shown in table 1a. The preliminary results were given by Jegede *et al.* (2004 a,b) and Mauder *et al.* (2007). Eleven days were considered in this investigation, nine days (DOYs 55, 56, 59, 60, 62, 64, 66, 67 and 68) were used for training, while two days (DOYs 57 and 65) were used for the verification of the models.

Diurnal averages of soil surface temperature, air temperature at 1 m and soil temperature at 5 cm for nine days with complete data sets were computed. Regression analyses were done between soil surface temperature and air temperature at 1 m, also between soil surface temperature and soil depth temperature at 5 cm using the averaged diurnal values.

The resulting empirical relations were used to retrieve the diurnal surface temperature for all the days. The performances of the models were also assessed on two day of year (DOY)s that were not included in their training period.

Table 1: List of equipment deployed during Nimex-1

Parameter	*Sensor*	*Accuracy*
Wind speed	Vector Instruments Cup anemometer A101ML/A100L2	1%
Wind direction	Vector Instruments Wind vane W200P	± 2^0
Wet and dry bulb air temperature	Theodor Friedrichs Frakenberger Psychrometer	± .05 ^{0}C
Soil surface temperature	Heitronics Infrared Pyrometer KT1582D	± 0.5^{0}C
Soil temperature	Campbell Scientific Thermistor Thermocouple	±1^{0}C
Soil heat flux	Hukseflux HFP01SC self calibrating Heat flux plate	±3%
Net radiation	Kipp and Zonen CNR1 net radiometer	±10% (daily total)
Volumetric soil moisture (%)	Campbell Scientific CS616 water content reflectometer	± 3% of water content
Data acquisition	Campbell Scientific Data-logger CR10X	Not applicable

Theory: The atmosphere does not readily absorb radiation at wavelengths between 0.3 and 1.0 μm, which is the region where the sun emits most of its energies (Ahren, 2007). The water vapor and carbon dioxide (CO_2) in the atmosphere are poor absorbers of visible solar radiation so they allow the passage of the sun's radiation to reach the earth surface. The air is not heated appreciably but the soil surface gets heated to the maximum since it behaves as a black body, it also emits the maximum possible energy at the infrared wavelengths. The CO_2 and the water vapor absorb energy in the infrared wavelength emitted by the soil surface, gain kinetic energy and consequently raise the temperature of the air near ground. The heated air becomes less dense and rises, cool and descends again. Consequently the air near the ground surface is kept constantly warmer than the air at higher level. The temperature of the air depends on the temperature of the soil surface. The heated soil surface also transfers heat into the deeper soil layers. The soil temperature at depths inside the soil also depends on the soil surface temperature.

Based on the theoretical knowledge of the relationship between the soil surface temperature and the air temperature near the ground, the null hypothesis that knowledge of air temperature near the ground suffices for an accurate estimation of surface temperature was developed. In the same vein a second hypothesis was also developed based on the fact that soil depth temperature depends on the soil surface temperature that knowledge of the soil depth temperature suffices for the accurate estimation of soil surface temperature.

Two independent regression models were developed, one for the determination of soil surface temperature from air temperature at 1 m height and the other for the determination of soil surface temperature from soil temperature at depth 5 cm.

Regression models: A linear relationship was assumed between the soil surface temperature and the air temperature at 1 m. The same relationship was assumed between soil surface temperature and the soil temperature at 5 cm depth. Two regression models of the following forms emerged from the nine days diurnal average of measured soil surface temperature, air temperature at 1 m height and soil temperature at 5 cm depth.

$$\hat{y}_1 = m_1 x_1 + c_1 \qquad (1)$$

$$\hat{y}_2 = m_2 x_2 + c_2 \qquad (2)$$

$\hat{y}_1$ *and* $\hat{y}_2$

are estimated soil surface temperatures, x_1 and x_2 are the independent variables which are air temperature at 1 m, and soil temperature at 5 cm respectively. m_1, m_2, c_1 *and* c_2, are unknown parameters which are slopes and intercepts of the trend lines on y axes respectively. Subscripts 1 and 2 represent values for air temperature regression and that for soil depth temperature regression respectively. The residual terms are omitted in equations (1) and (2). The m's and c's can be found from the following equations:

$$m = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sum (x_i - \bar{x})^2} \qquad (3)$$

$$c = \bar{y} - m\bar{x} \qquad (4)$$

The residual term is given by

$$\varepsilon_i = y_i - \hat{y}_i \qquad (5)$$

y_i is the measured value of soil surface temperature.

Goodness of fit: The bias error, the mean absolute error (MAE), the root mean squared error (RMSE), the t test statistic, the chi square statistic and the coefficient of determination were computed to assess the goodness of fit of the two models.

The bias error was given by equation (5).

The MAE was given by the mean of the absolute value of the bias error

$$MAE = \left| \frac{y_i - \hat{y}_i}{n} \right| \qquad (5a)$$

n = number of samples

The RMSE was given by the square root of the mean of the squared bias error;

$$RMSE = \sqrt{\frac{(y_i - \hat{y}_i)^2}{n}} \qquad (5b)$$

The t value was given by:

$$t = \frac{\bar{y}_1 - \bar{y}_2}{\sigma_d} \qquad (5c)$$

$$\sigma_d = \sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}} \qquad (5d)$$

is the square root of the variance of the difference between means of the two sets of data being compared.

$\bar{y}$

is the mean of a data set.

Subscripts 1 and 2 are for the first and second set of data respectively. (Observed and estimated data set in any order)

The Chi square was given by:

$$\chi^2 = \sum \frac{(observed\ frequency - \exp ected\ frequency)^2}{\exp ected\ frequency} \qquad (5e)$$

The coefficient of determination is the square of the Pearson product moment correlation coefficient given by:

$$R^2 = \left(\frac{\sum_{i=1}^{n} (y_{1i} - \bar{y}_1)(y_{2i} - \bar{y}_2)}{\sqrt{\sum_{i=1}^{n} (y_{1i} - \bar{y}_1)^2} \sqrt{\sum_{i=1}^{n} (y_{2i} - \bar{y}_2)^2}} \right)^2 \qquad (5f)$$

RESULTS AND DISCUSSION

Result of air temperature regression model (Model 1): The values for m_1 and c_1 obtained, using air temperature at 1 m were 1.347 and 2.0969 respectively with R^2 value of 0.99. Equation (1) then becomes:

$$\hat{y}_1 = 1.347x_1 + 2.0969 \qquad (1b)$$

This equation was used to estimate the soil surface temperature for DOYs 55, 56, 59, 60, 62, 64, 66, 67, and 68. Table 2 showed the soil moisture contents (0 – 5 cm) and wind speed at 0.7 m and 1.2 m heights. The estimated soil surface temperature values compared well with the measured ones (Figure I and Table 3). The coefficient of determination (R^2) between the estimated soil surface temperature values and the measured ones (with trend lines at the origin) ranged between 0.92 and 0.99. The MAE between the measured and estimated soil surface temperature ranged between 0.65 and 2.48^{0}C, while the RMSE ranged between 0.81 and 2.63^{0}C (Table 3).

Table 2: Variations of soil moisture and wind speed during the period of Nimex-1

DOY	*Soil moisture(daily range)*	*Wind speed (0.7m)*	*Wind speed (1.2 m)*
	(cm^3/cm^3)	(ms^{-1})	(ms^{-1})
55	0.04-0.05	0.71	0.83
56	0.04-0.20	0.89	1.83
57	0.11-0.24	0.85	0.96
59	0.13-0.15	0.61	0.69
60	0.11-0.16	0.77	0.88
62	0.12-0.13	0.92	1.05
64	0.10-0.11	0.78	0.91
65	0.09-0.10	1.00	1.18
66	0.08-0.09	0.93	1.10
67	0.08-0.09	0.69	0.83
68	0.74-0.08	0.51	0.62

The student t test values ranged between 0.02 and 2.09. The Chi square values ranged from 0.68 to 2.94. The Chi square and most of the t- values were not significant at 5% significant level so the null hypothesis is accepted. The soil field capacity (θ_{fc}) for loamy sand is given as 0.15 (Lee and Pielke, 1992). Using the assumption of these authors that all soils should behave the same way at some fixed soil water characteristics, the dependence of the wetness function on the soil texture was eliminated by choosing the soil field capacity as the point where the soil surface specific humidity will begin to change. The equation (1b) could be used at nearby tropical stations under similar weather conditions and $\theta \leq \theta_{fc}$ for any soil with measured air temperature at 1 m level to estimate soil surface temperatures that could be of use in other models.

Table 3: Statistics between measured and observed soil surface temperature with air temperature as predictor

Statistics DOY	*R^2*	*MAE* (^{0}C)	*RMSE* (^{0}C)	*Chi^2*	*t*
55	0.97	2.30	2.41	7.50	1.95
56	0.97	2.48	2.63	8.91	2.09
59	0.95	1.50	1.92	4.37	1.35
60	0.94	1.09	1.53	2.95	0.67
62	0.92	0.98	1.30	2.01	0.94
64	0.98	0.64	0.77	0.68	0.02
66	0.99	0.65	0.81	0.99	0.39
67	0.97	1.00	1.22	1.78	0.48
68	0.97	1.18	1.41	2.85	0.52

DOY 57 was the only DOY with $\theta > \theta_{fc}$, (Table 2) but the estimated soil surface temperature was not significantly different from the measured one. DOY 56 was characterized by low soil moisture ($\theta < \theta_{fc}$) but the highest wind speed. The value of the wind speed affected the performance of the model despite the low θ. The model can also be affected by the vegetation level, however the experiment was carried out on bare soil and this eliminated the effect of vegetation height.

Ability of the model to predict accurate soil surface temperature depends on the conformity of the synoptic weather or the prevailing weather on a particular day to the average prevailing weather condition, especially the wind speed during the training period of the model. The vegetation height, soil moisture and wind speed should conform to the situation on the Nimex-1 field. The measurements were taken on bare soil. The period of the DOYs is a transition period from dry to wet season, when there were few rains and drizzle, low wind speed and low soil moisture (Table 2). On the average, the weather was fair and dry ($\theta \leq \theta_{fc}$) , bare soil or very low vegetation height, wind speed ≤ 1.8 ms^{-1}. On DOY 55, the soil moisture and the wind speed were low, the R^2 value was high, MAE and RMSE were low and Chi square value was not significant at the 5% level. The t value was less than the critical value of 1.99. There was a slight drizzle, but the performance of the model was excellent since the wind speed was low (< 1.0 ms^{-1}) (Table 2).

On DOY 56 there was a heavy rain storm for about 30 minutes (between 19.30 and 20.00 hrs Local time). The soil moisture was low but the wind speed was the highest among the DOYs (1.83 ms^{-1}). The wind speed and rainstorm constituted a perturbation in the physics of heat transferred at that period. The R^2 value was high (0.97), the error values were not high (2.48 and 2.63 respectively) for MAE and RMSE. The chi square value was not significant at the 5% level, but the t value was significant at the 5% level but not significant at higher levels.

The other DOYs had similar weather conditions with the average weather acceptable to the model (under which the model was trained) so that the estimations were perfect with high R^2 values, low MAE and RMSE values, insignificant chi square and t values (Table 3).

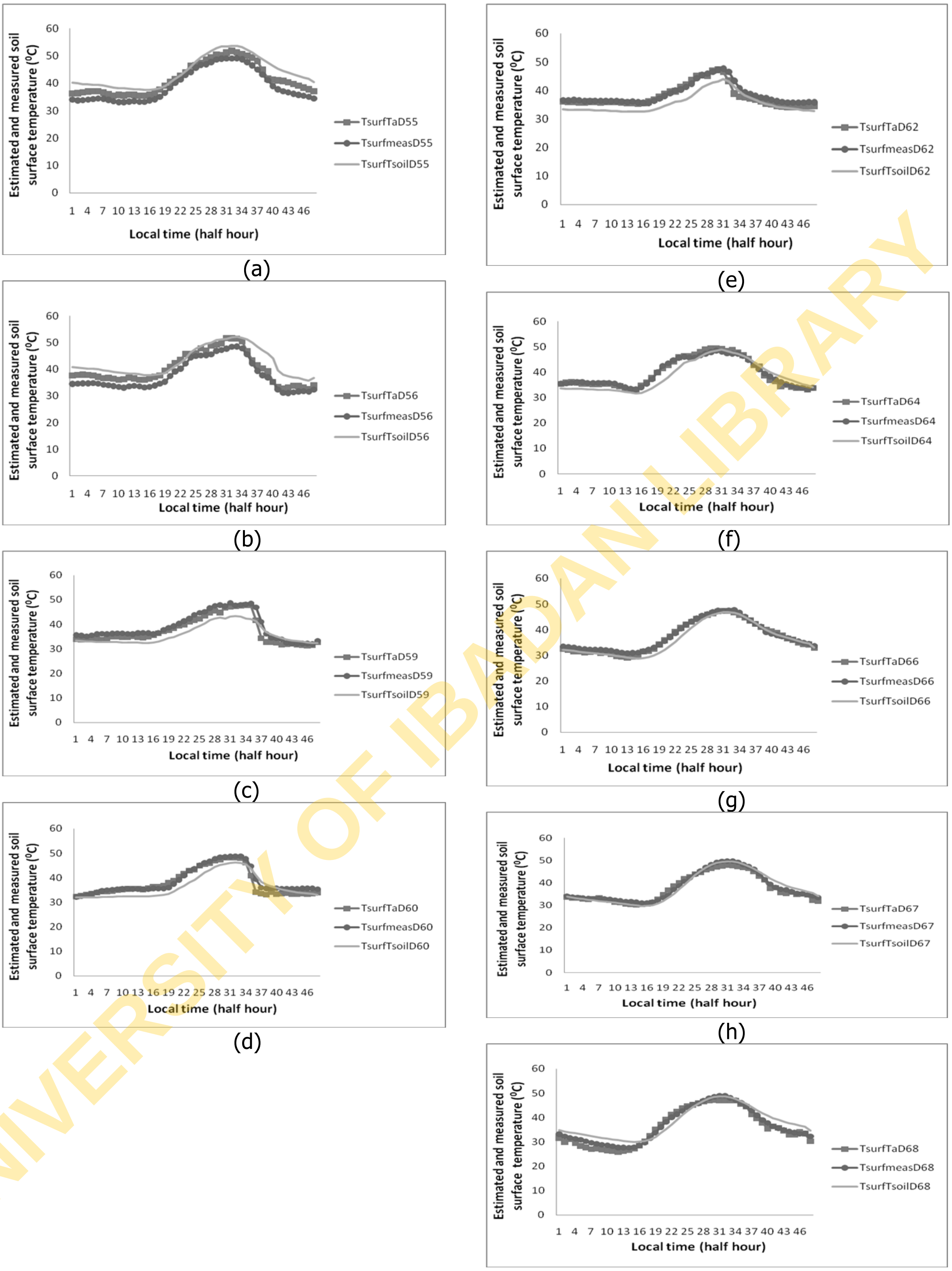
It is possible to estimate soil surface temperature from air temperature at 1 m height provided the model used was built under similar weather condition with the DOY on which estimation of soil surface temperature is required.

Result for soil depth temperature Regression model (model 2): The regression coefficients *m_2* and *c_2* obtained for the regression between soil temperature at 5 cm depth and the soil surface temperature were 1.422 and -5.269. The coefficient of determination was found to be 0.935, which is is lower than that obtained from air temperature regression.

The linear regression equation is:

$$\hat{y}_2 = 1.422x_2 - 5.269 \qquad (2b)$$

Model 2 (with soil temperature at 5 cm as s predictor) was more sensitive to the prevailing weather conditions. When there is contrast between the condition by which the model was trained and the prevailing weather condition on a particular DOY, the t value becomes significant at the 5% level though not significant at higher levels. DOYs 55, 56, 59 and 62 had significant t values at 5% level though the chi square values were not.



(a) (b) (c) (d) (e) (f) (g) (h) (i)

Fig. I: Diurnal variation of estimated and measured soil surface temperature (⁰C) at Nimex 1 site in 2004. (TsurfTa=soil surface temperature predicted from air temperature; TsurfTsoil=soil surface temperature predicted from soil depth temperature and Tsurfmeas=measured soil surface temperature).

Their R^2 values were high, and their MAE and RMSE values were not very high (Table 4). There was slight drizzle on DOY 55 and 62, heavy rain on DOY 56, no rain on DOY 59. The drizzle and rain storm affected the performance of the model on those days. The remaining DOYs had high R^2 values, low MAE and RMSE values. The chi square and t values were all less than the critical values at 5% significant level. Knowing the values of soil temperature at 5 cm depth suffices for the estimation of diurnal soil surface temperature.

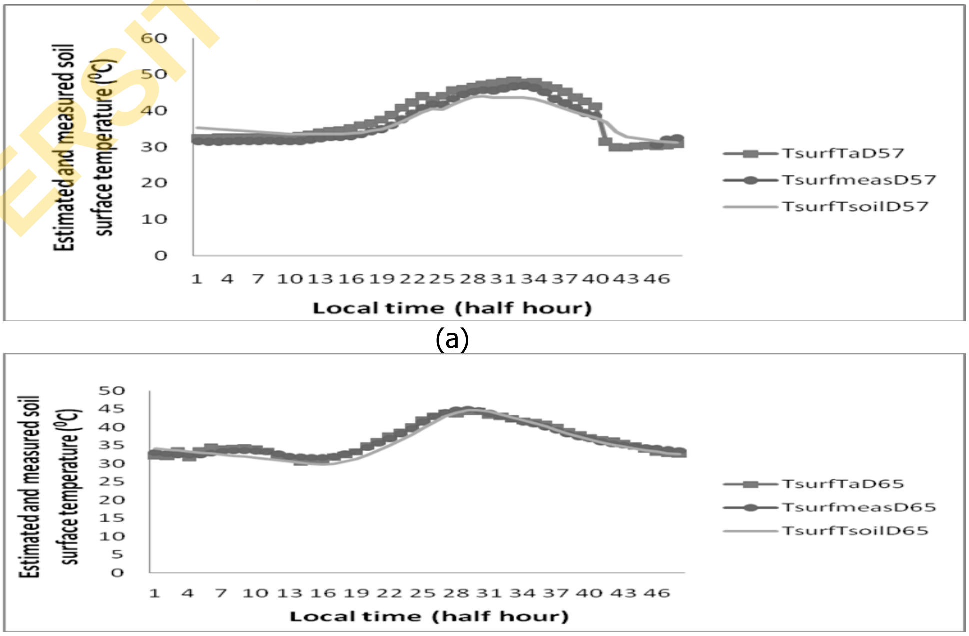
Generally the coefficients of determination with air temperature as predictor were higher than those with soil temperature at 5 cm as predictor. Also, the MAE and RMSE values with air temperature as predictor were lower than those for soil temperature as predictor. The first model was found to be more efficient in predicting soil surface temperature than the second one during the transition period.

Table 4: Statistics between measured and observed soil surface temperature with soil temperature at 5 cm depth as predictor

Statistics	*R^2*	*MAE*	*RMSE*	*Chi^2*	*t*
DOY		^{0}C	^{0}C		
55	0.87	4.71	4.98	31.84	4.00
56	0.84	4.94	5.25	36.74	4.34
59	0.75	3.41	3.81	16.61	3.13
60	0.91	2.43	2.69	8.71	2.08
62	0.94	3.07	3.20	12.58	4.21
64	0.86	2.01	2.44	7.31	0.93
66	0.96	1.39	1.75	4.45	1.05
67	0.96	1.05	1.28	2.22	0.11
68	0.90	1.96	2.24	7.30	0.88

The results of the two models are comparable to published surface temperature estimations in other study areas using different methods. Mihailovic *et al.* (1999) obtained MAE and RMSE values between measured and estimated soil surface temperature ranging from 1.8 - 2.25 and 2.3 - 2.7^{0}C respectively from five different force restore models. Mallick *et al.* (2008) arrived at lower correlation coefficients between measured and estimated soil surface temperature over bare soil in Delhi using two different methods to estimate soil surface temperature from Landsat-7 ETM+ data. Raj and Fleming (2008) obtained a difference of 1 - 2^{0}C between estimated and measured soil surface temperature as well as an RMSE value of 1.13^{0}C.

Verification of the models: DOYs 57 and 65 were not included in the training period of the two models. The two models gave reliable estimation of soil surface temperature on the two DOYs (Figure II).



(a)

(b)

Fig. II: Diurnal variation of estimated and measured soil surface temperature for DOYs 57 and 65

The R^2 value between measured and estimated soil surface temperature were 0.97 and 0.77 for air temperature model and soil depth temperature respectively on DOY 57. The MAE and RMSE values were1.80 and 1.96 respectively for model 1, while the values were 1.72 and 1.99 respectively for model 2. DOY 65 also had high R^2 values; they were 0.97 and 0.95 for models 1 and 2 respectively. The MAE and RMSE values were 0.62 and 0.72 for model 1, while they were 1.04 and 1.25 for model 2 respectively for DOY 65. The t values were also 0.04 and 0.80 for models 1 and 2 respectively. The t and X^2 values were not significant at 5% significant level.

There was no rain on DOY 65 but there was short lived rainstorm on DOY 57, nevertheless the models performed excellently on both DOYs. On DOY 57, the average θ was still less than θ_{fc} although it was greater at some period, nevertheless the wind speed was less than 1 ms^{-1}, and the soil moisture did not affect the performance of the models because of the low wind speed. The X^2 values for model 1 were 4.34 and 0.73 for DOY 57 and 65 respectively, while they were 4.71 and 2.16 for model 2. The student-t test values were 0.59 and 0.04 for model 1 on DOYs 57 and 65 respectively, while they were 0.34 and 0.8 for model 2.

Applicability of Models 1 and 2: The two models are applicable in the tropics, especially during the transition period when there is little or no rain. The soil at the experimental field is loamy sand, but the models can be applied to other soils, with soil moisture that is less than or equal to θ_{fc}. Soil field capacity (θ_{fc}) removed the dependency of the models on soil structure. Model 1 is more resistant to the prevailing weather than model 2, but they both performed excellently when the weather was not perturbed by wind, rain storm or drizzle. The prevailing weather should be considered for the DOYs and compared with the mean values under which the models were trained (Table 2). Nearby stations could specifically benefit from these models if sensors for soil surface temperature are not available there.

CONCLUSION

Using air temperature at 1 m and soil temperature at 5 cm as separate predictors resulted into efficient models for estimating soil surface temperature for bare soil in the humid tropical area during the transition period. Knowledge of either air temperature at 1 m or soil temperature at 5 cm depth was found to be adequate for the estimation of soil surface temperature for this area provided the prevailing weather condition for the day on which the soil surface temperature is to be estimated is similar to the mean weather condition under which the models were constructed. The models were more efficient when the weather was fair and dry, with little or no rain.

ACKNOWLEDGEMENT

We acknowledge the support given to us by fellow Nimex group members. We are also grateful to the following bodies for their support in providing the equipment and research funds for the experiment: International Programs in the Physical Sciences (IPPS) Sweden; African Regional Centre for Space Sciences and Technology Education, Ile- Ife, Nigeria and National Space Research and Development Agency, Abuja, Nigeria. This study was carried out at the Abdus Salam International Center for Theoretical Physics, Trieste, Italy.

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