

Soil temperature prediction from air temperature for alluvial soils in lower Indo-Gangetic plain

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A b s t r a c t. Soil temperature is an important factor in biogeochemical processes. On-site monitoring of soil temperature is limited in spatio-temporal scale as compared to air temperature data inventories due to various management difficulties. Therefore, empirical models were developed by taking 30-year long-term (1985-2014) air and soil temperature data for prediction of soil temperatures at three depths (5, 15, 30 cm) in morning (0636 Indian standard time) and afternoon (1336 Indian standard time) for alluvial soils in lower Indo-Gangetic plain. At 5 cm depth, power and exponential regression models were best fitted for daily data in morning and afternoon, respectively, but it was reverse at 15 cm. However, at 30 cm, exponential models were best fitted for both the times. Regression analysis revealed that in morning for all three depths and in afternoon for 30 cm depth, soil temperatures (daily, weekly, and monthly) could be predicted more efficiently with the help of corresponding mean air temperature than that of maximum and minimum. However, in afternoon, prediction of soil temperature at 5 and 15 cm depths were more precised for all the time intervals when maximum air temperature was used, except for weekly soil temperature at 15 cm, where the use of mean air temperature gave better prediction.

K e y w o r d s: soil temperature, air temperature, regression analysis, alluvial soil, Indo-Gangetic plain

INTRODUCTION

Soil temperature is an important factor in seed germination (Dwyer *et al.*, 1990), root growth (Kaspar and Bland, 1992), root respiration (Burton *et al.*, 1998), and water and nutrient uptake by plants (Kaspar and Bland, 1992). It also influences biological processes of soil inhabitants like insects and other soil organisms (Kluender *et al.*, 1993; McCann *et al.*, 1991). It directly and indirectly affects soil physical processes like infiltration (Singh, 1992), hydraulic conductivity (Ren *et al.*, 2014), and movement

of nutrients and chemicals (solute movement) in soil profiles (Grundmann *et al.*, 1995; Vigil and Kissel, 1995). As solute concentration is affected by soil temperature, it controls their movements in soils (Merdun, 2012). Apart from this, soil temperature controls biogeochemical processes such as dissolved organic carbon export (Haei *et al.*, 2010), its residence time in soils (Euskirchen, 2006; Oquist and Laudon, 2008), rates of mineralization (Haei *et al.*, 2013; Rustad *et al.*, 2001) and/or decomposition of soil organic matter (Davidson and Janssens, 2006; Domisch *et al.*, 2001; Melillo *et al.*, 2002) as well as forest productivity (Stromgren and Linder, 2002). Soil temperature has a direct relationship with decomposition of organic matter and soil respiration (Leirós *et al.*, 1999). Considering its significant contribution in soil weathering process, soil temperature regime has been included as classification criteria in the Soil Taxonomy (Gislason *et al.*, 2009; Soil Survey Staff, 1999).

Air temperature is one of the important climatic parameters, which is directly related to soil temperature. It has been observed that the global warming effects is not only restricted to air temperature but also change soil temperature as well as precipitation patterns (Jungqvist *et al.*, 2014). As the soil temperature is influenced by various soil and moisture regimes and *vis-a-versa*, its response to climate change differs from that of air temperature (Zhang *et al.*, 2005). At the same time, studies on climate change and carbon sequestration also need reliable data on soil temperature (Brenna *et al.*, 2002). As the measurement of soil temperature is limited in spatio-temporal scale, air temperature has often been used to estimate soil temperature by several researchers

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(Gupta *et al.*, 1983; Hasfurther and Burman, 1974; Toy *et al.*, 1978; Zheng, 1993). Soil temperature although integral in many biogeochemical processes in ecosystem, is often difficult to monitor in spatio-temporal levels as installation of soil temperature measuring equipment in soil profile not only a costly affair but also tedious. Developing suitable site specific model to predict soil temperature from air temperature could decrease the amount of time, energy, and cost necessary for on-site monitoring of soil temperature. Empirical model fairly predicts soil temperature from air temperature along with some related parameters (Kang *et al.*, 2000), but it requires to develop for specific sites considering prevailing soil moisture, land use and climate condition. In addition, linking of soil and air temperature data of permanent weather station envisaged understanding of temporal and spatial variation in soil temperature in relation to climate change pattern. Keeping this in view the objective of this study was to develop suitable regression model to estimate and predicts the soil temperatures at different soil depths by using the long-term air temperature data.

MATERIALS AND METHODS

The study site falls under new alluvial zone (soil type: Ustoccept) which is one of the six agro-climatic zones, viz. hill zone, terai zone, old alluvial zone, new alluvial zone, red and laterite zone, and coastal and saline zone in West Bengal (eastern state) of India. The long-term average annual rainfall (1976-2015) at the site was 1552.3 mm (ranges between 923.9 and 2253.6 mm), 73.3% of which precipitated during the months of June to September (monsoon), 14.3% during March to May (pre-monsoon), 10.2% during October to December (post-monsoon) and 2.2% during January to February (winter). The mean annual maximum and minimum temperatures were 31.1 and 20.8°C, respectively. The climate of the study site is sub-tropical and humid.

Long-term data of air and soil temperature for the period of 30 years (1985-2014) were collected from the Agrometeorology Section of ICAR-Central Research Institute for Jute and Allied Fibres (ICAR-CRIJAF), Barrackpore, Kolkata. The agrometeorological observatory is situated at 22°45'16.53" N and 88°25'19.25" E and 9.69 m above mean sea level. Stevenson screen installed at 1.2 m height was used to record air temperature data, and bare soil temperature data were recorded with mercury soil thermometers installed at 5, 15, and 30 cm soil depths. Both air and soil temperatures data were recorded daily at two fixed times, first was in the morning at 0636 IST and second one in the afternoon at 1336 IST. The morning reading represented the minimum and the afternoon reading to the maximum values of temperature. Daily data of soil temperatures at three depths (5, 15, and 30 cm) and air temperatures were converted to weekly, monthly, and annual means by recommended statistical analysis. Soil tem-

perature data were taken up to 30 cm depth because temperature changes primarily occurred within that depth of soil in a temporal and spatial scale, while beyond 40-60 cm soil depth the change in soil temperature becomes non-significant (Scheffer *et al.*, 2002).

Soil samples at 5, 15, and 30 cm depths were collected from four random points within 1 m radius circle by keeping soil thermometers at or near the centre of the circle. The composite soil samples for each soil depth were made by quartering method and air dried. Air dried samples were passed through 2 mm sieve before analysis of soil texture in laboratory by following hydrometer method (Bouyoucos, 1962). Sand, silt, and clay percentages in soils were 26.04, 56.16, and 7.80 at 5 cm depth; 42.04, 36.08, and 21.88 at 15 cm depth; and 49.96, 26.08, and 23.96 at 30 cm depth, respectively. The corresponding textural classes were silty loam, loam, and sandy loam at 5, 15, and 30 cm depths, respectively.

The mean, standard deviation and coefficient of variation were calculated by using the following equations:

$$T_m = \sum (X_i/n), \quad (1)$$

$$\sigma = \sqrt{[\{X_i - (\sum (X_i/n))^2/n\}}, \quad (2)$$

$$\text{coefficient of variation (CV, \%)} = (\sigma/T_m) 100\%, \quad (3)$$

where: T_m is the mean air or soil temperature, X_i is the air or soil temperature of i number of weeks, months, seasons or years, ($i=1, 2, \dots, n$); n is the total number of weeks, months, seasons or years for which temperature data is being analyzed; σ is standard deviation of i numbers of time period.

In this study, the magnitude of trend in the temperature time series was determined using a non-parametric method (Theil, 1950) known as Theil-Sen estimator or Sen slope estimator (Sen, 1968). Sen method assumes a linear trend in the time series and has been widely used for determining the magnitude of trend in hydro-meteorological time series (Kumar *et al.*, 2014; Pal *et al.*, 2015). By using this method, the true slope (change per unit time) can be estimated by using a simple non-parametric procedure. To derive an estimate of the slope in a linear model:

$$f(t) = Qt + B, \quad (4)$$

where: B is a constant, the slopes of all data pairs are calculated as:

$$Q_i = \frac{x_j - x_k}{j - k}, i = 1, 2, \dots, N, \quad (5)$$

where: x_j and x_k are data values at time, j and k ($j > k$), respectively. The median of these N values of Q_i is Sen estimator (Q) of slope. A positive value of Q indicates an upward (increasing) trend and a negative value indicates a downward (decreasing) trend in the time series.

To determine whether the trend obtained from Sen slope estimator is statistically significant or not, non-parametric Mann-Kendall (M-K) test (Kendall, 1975; Mann, 1945) was employed in the present study. According to this test, the null hypothesis H_0 assumes that there is no trend. The alternative hypothesis H_1 is that the data follow an increasing or decreasing monotonic trend over time. If a data value from a later time period is higher (lower) than a data value from an earlier time period, the M-K statistic is incremented (decremented) by 1. The standard test statistic Z was computed and was approximately normally distributed. The presence of a statistically significant trend was evaluated using the Z value. A positive (negative) value of Z indicates an upward (downward) trend. If the computed value of $|Z| > Z_{\alpha/2}$, the null hypothesis (H_0) is rejected at α level of significance in a two-sided test. The corresponding p value was calculated at 5% significance level.

Different non-linear statistical models were used to predict soil temperature (Y_t) at time point $t = 1, 2, \dots, n$ using air temperature as the predictor variable. By this way, we obtained predicted soil temperature (\hat{Y}_t) at all the time points for the power, exponential and logarithmic models. The lower and upper limits of prediction interval for all the observations were computed statistically at 95% confidence level.

RESULTS AND DISCUSSION

The characteristics of both air and soil temperatures were analyzed for daily, weekly, and monthly data to develop their corresponding relationships. The average of 30 years (1985-2014) of daily minimum, maximum, and mean air temperatures followed the similar pattern (Fig. 1). The scrutiny of 30 years averaged daily air temperature data showed that the lowest minimum, maximum, and mean temperatures were 10.05, 23.69, and 16.88°C, respectively and their respective highest values were 26.54, 36.47, and 31.09°C. The coefficients of variation (CV) for minimum air temperature were higher (ranged from 2.82 to 32.93%) than that of maximum air temperature (ranged from 3.53 to 11.85%), which indicated that maximum temperatures over the last three decades were more consistent than minimum temperature. When daily air temperature data were converted to weekly time scale by statistical mean, its 30 years average data also showed the similar trend like daily data. Weekly lowest minimum (10.41°C), maximum (23.95°C), and mean (17.18°C) air temperatures were observed at first week (1-7 January) of a calendar year, whereas highest values for both the minimum (25.95°C) and mean (30.71°C) temperatures were found at 22nd week (28 May to 3 June) but for maximum (35.85°C) it was at 16th week (16-22 April). Similar to the variability of daily air temperature, CV values of weekly minimum temperature were higher (ranged from 2.01 to 21.72%) than that of maximum temperatures (2.44 to 7.51%). Among the 52 weeks in a year,

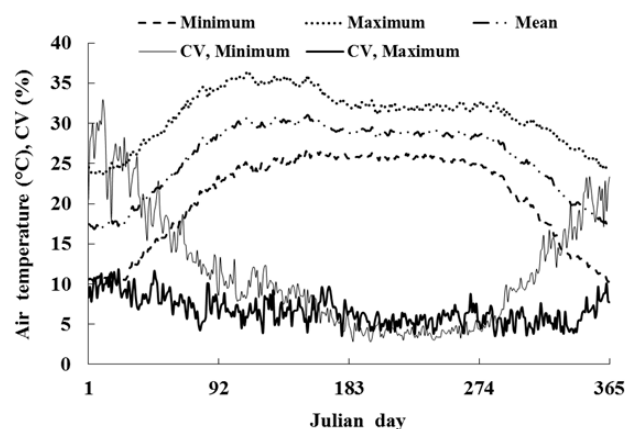


Fig. 1. Daily air temperature pattern of 30 years average data (1985-2014) with their coefficient of variation in lower Indo-Gangetic plain.

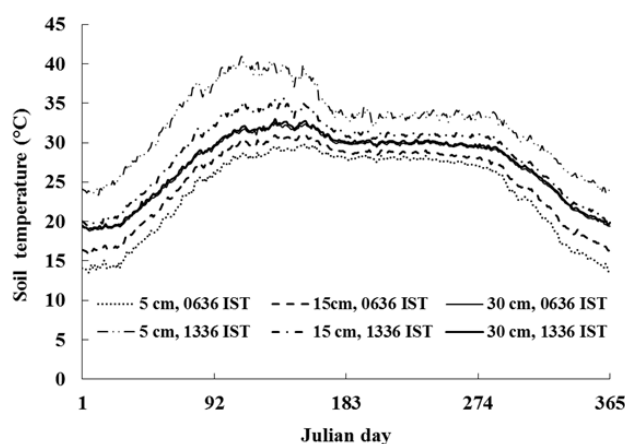


Fig. 2. Daily soil temperature pattern in morning (at 0636 IST) and afternoon (at 1336 IST) at different depths for alluvial soils in lower Indo-Gangetic plain.

the CV values of minimum and maximum air temperature were respectively lowest on 27th week (2-8 July) and 29th week (16-22 July) because during this period air temperature fluctuation was lesser than rest of a year due to the south-west monsoon rain that generally starts on about 2nd week of June (Barman *et al.*, 2012).

Like daily air temperature average of 30 years daily soil temperatures at each depth of 5, 15, and 30 cm in morning (at 0636 IST) and afternoon (at 1336 IST) plotted against the days of year and it was found that soil temperature followed the similar pattern of air temperature (Fig. 2). However, the magnitude of soil temperatures were different than that of air temperature; average daily soil temperatures at 5, 15, and 30 cm soil depths in morning were about 2.97, 4.51, and 6.30°C higher, respectively, than minimum air temperature, whereas in afternoon soil temperatures were 1.48°C higher at 5 cm but 2.25 and 3.62°C lower, respectively at 15 and 30 cm soil depths than corresponding maximum air temperature. Dwyer *et al.* (1990) also observed that average daily soil temperature at 5 cm depth were about 2.0

and 1.5°C higher than corresponding minimum and maximum air temperatures, respectively. Toy *et al.* (1978) also found similar results in their experiment with different soil types and attributed the reasons to the 'low specific heat' and 'reduced air mixing' in soils than in air just above the soil surface. From Fig. 2, it was evident that in morning average daily soil temperature of surface soils at 5 cm depth was lowest, and it increased gradually with depth in subsurface soils (at 15 and 30 cm) due to relatively faster cooling of surface soil during night time than subsurface soils when there was no energy source of solar radiation. Unlike morning, soil temperatures in afternoon followed the reverse trend with depths, because, with the progress of a day, heat transformation from direct solar radiation and advection of hot air increased surface soil temperature faster than its subsequent dissipation of heat to increase temperature in subsurface soil layers by conduction method of heat transmission. Similar trend was also observed in weekly and monthly data (data not shown). Kang *et al.* (2000) reported the similar results. For all the three soil depths weekly lowest temperatures in both the cases of morning and afternoon were found at 1st week except for 30 cm depth in morning where it was found at 2nd week (8-14 January). In morning at 5, 15, and 30 cm depths, weekly lowest minimum temperatures were 13.98, 16.31, and 19.25°C, respectively, whereas, in afternoon the respective lowest temperatures were 23.57, 19.48, and 19.21°C. Weekly highest temperature in morning at 5, 15, and 30 cm soil depths were observed at week number 23rd (4-10 June), 22nd (28 May – 3 June) and 20th (14-20 May), respectively, whereas, in afternoon for 5 cm depth it was observed at 16th week (16-22 April) and for 15 and 30 cm depths at 20th week. In the respective depths, the values were 29.56, 30.80, and 32.52°C in morning and 39.89, 34.83, and 32.44°C in afternoon. As heating (in day) and cooling (in night) process occurred through the surface soil, temperature in afternoon and morning generally fluctuated more at surface soil (5 cm) than subsurface soils (15 and 30 cm), which was corroborated by the highest CV values of 10.43 in afternoon and 12.32 in morning at surface soil.

Monthly and annual minimum, maximum and mean air temperature data of 30 years (1985-2014) average along with their descriptive statistics were presented in Table 1. This table showed that average monthly minimum (10.82°C), maximum (24.49°C), and mean (17.66°C) air temperatures were lowest in January that appeared as the coolest month in a calendar year, and May was identified as the warmest month due to its highest maximum (35.09) and mean (30.15) temperatures. Similar findings about the hottest and coolest month were also observed at the same study site by analyzing 10 years (2001-2010) data (Barman *et al.*, 2012). The fluctuation of minimum and mean air temperatures during last three decades (1985-2014) was highest in January, which was evident by highest CV values of 10.29% and 7.35%, respectively; whereas for maxi-

imum air temperature it was highest in February (Table 1). But for all three temperatures, minimum fluctuations was observed in July, which may be attributed to the monsoon rain. The trend analyses of time series weekly and monthly air temperature data were performed but only the results of monthly data were presented in Table 2. From this table, it was evident that a significant monotonically decreasing trend (-0.018°C y⁻¹) of minimum temperature has been detected in the month of August over the period of 1985-2014. In general, average minimum air temperature was in decreasing trend for most of the months but it was reverse in the case of maximum temperature. In trend analysis by taking weekly data (data not shown), significant monotonically decreasing trend of -0.128, -0.028, -0.025, -0.070 and -0.061°C per year was observed in week number 2, 33, 34, 44 and 52, respectively, in the case of minimum temperature over the study period.

Mean monthly soil temperature data of 30 years at two fixed times (0636 IST and 1336 IST) for three soil depths (5, 15 and 30 cm) are presented in Table 3. At all the three soil depths, minimum soil temperature was observed in January, and maximum was in May at both the times, which followed similar trend with corresponding values of the air temperatures. In morning (at 0636 IST) at 5, 15, and 30 cm soil depths, monthly minimum soil temperatures were 14.4, 17.0, and 19.1°C; and maximum were 28.9, 30.8, and 31.8°C, respectively. And, in afternoon (at 1336 IST) at the same soil depths, minimum soil temperatures were 24.4, 20.2, and 19.1°C; and maximum were 39.0, 34.6, and 32.2°C, respectively. In general, average annual soil temperatures at 5, 15, and 30 cm soil depths were about 8.62, 3.92, and 0.17°C higher in afternoon than in morning, respectively at 5, 15 and 30 cm soil depths. From the coefficients of variation in Table 3, it was evident that the fluctuation in average monthly soil temperatures at 5 cm depth in afternoon were higher than in morning, whereas it was generally reverse in the case of 15 and 30 cm soil depths. The results of the trend analysis of monthly soil temperatures over 30 years (1985-2014) were presented as Sen's slope and p-value in Table 4. In general at 5 cm depth, significant monotonically increasing and decreasing trends were observed in morning and afternoon, respectively.

Empirical models based on regression analysis were developed by taking 30 years averaged daily maximum and mean air temperature data with daily soil temperature data at 5, 15, and 30 cm depths for both morning and afternoon (Fig. 3). The purpose of using the long-term data in developing the models was to reduce bias in prediction and yearly variability in temperature due to climate and soil factors as suggested by Dwyer *et al.* (1990). It was observed that daily mean air temperature could be used to predict soil temperature in morning (0636 IST) by best fitted power model at 5 cm soil depth with R² = 0.993; whereas, exponential models were best suited at 15 and 30 cm depths, with R² values of 0.997 and 0.993, respectively. The

Table 1. Descriptive statistics of monthly minimum (Tmin), maximum (Tmax) and mean (Tmean) air temperature data (monthly average of 1985-2014) in Indo-Gangetic plain

Statistics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Tmin (°C)													
Mean	10.82	14.61	19.68	23.95	25.20	26.02	25.91	25.86	25.25	22.84	17.64	12.21	20.83
SD	1.11	0.97	1.62	1.08	0.82	0.72	0.49	0.55	0.58	0.83	1.22	0.97	0.42
CV (%)	10.29	6.66	8.23	4.51	3.25	2.79	1.90	2.14	2.30	3.61	6.89	7.93	2.02
Tmax (°C)													
Mean	24.49	28.07	32.88	35.37	35.09	33.70	32.11	32.00	31.98	31.46	29.17	25.81	31.00
SD	1.08	1.38	1.29	1.35	1.01	1.06	0.49	0.54	0.51	0.62	0.66	0.68	0.36
CV (%)	4.41	4.91	3.92	3.81	2.89	3.14	1.54	1.69	1.60	1.97	2.28	2.62	1.17
Tmean (°C)													
Mean	17.66	21.34	26.28	29.66	30.15	29.86	29.01	28.93	28.62	27.15	23.40	19.01	25.91
SD	1.10	1.17	1.45	1.21	0.92	0.89	0.49	0.55	0.55	0.72	0.94	0.82	0.30
CV (%)	7.35	5.78	6.08	4.16	3.07	2.96	1.72	1.91	1.95	2.79	4.58	5.28	1.15

Table 2. Sen slope (Q) (°C y^{-1}) and p value ($p = 0.05$) for the trend of Mann-Kendall test for monthly minimum, maximum, and mean air temperature over the period of 1985-2014

Month	Tmin		Tmax		Tmean	
	Q	p value	Q	p value	Q	p value
January	-0.011	0.761	-0.037	0.101	-0.025	0.253
February	-0.014	0.655	0.000	1.000	0.008	0.735
March	-0.007	0.844	0.022	0.326	0.009	0.789
April	0.000	1.000	-0.005	0.957	-0.004	0.915
May	-0.008	0.668	0.018	0.411	0.005	0.748
June	0.003	0.802	0.018	0.422	0.011	0.617
July	-0.001	0.844	0.006	0.485	0.003	0.579
August	-0.018	0.012*	0.000	0.844	-0.014	0.093
September	-0.014	0.246	0.006	0.475	-0.003	0.748
October	-0.022	0.268	-0.004	0.721	-0.010	0.326
November	-0.027	0.232	0.013	0.246	-0.008	0.509
December	-0.018	0.421	-0.021	0.128	-0.019	0.186

*significant at 5% level.

Table 3. Descriptive statistics of average monthly soil temperature data (monthly average of 1985-2014) at different depths in alluvial soils in Indo-Gangetic plain

Statistics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Morning (0636 IST)													
Depth 5 cm													
Mean	14.36	18.00	23.55	27.62	28.88	28.90	27.89	27.71	27.33	25.24	20.33	15.38	23.77
SD	1.00	1.04	1.15	1.48	1.38	0.87	0.64	1.09	0.61	0.87	1.18	0.86	0.51
CV (%)	6.98	5.77	4.90	5.37	4.77	2.99	2.29	3.92	2.22	3.46	5.78	5.59	2.13
Depth 15 cm													
Mean	17.03	20.41	25.80	29.74	30.78	30.23	28.77	28.85	28.59	26.52	22.35	17.88	25.58
SD	1.94	2.39	2.05	2.25	2.12	1.91	1.11	1.49	1.33	0.78	1.05	0.85	1.20
CV (%)	11.38	11.73	7.96	7.58	6.87	6.33	3.85	5.17	4.67	2.96	4.68	4.74	4.68
Depth 30 cm													
Mean	19.14	22.29	27.17	30.75	31.85	31.11	29.70	29.64	29.59	28.37	24.88	21.20	27.14
SD	0.74	0.89	1.07	1.46	1.11	0.98	0.60	1.24	0.52	0.70	0.81	2.41	0.40
CV (%)	3.84	4.00	3.93	4.74	3.47	3.16	2.03	4.19	1.75	2.47	3.25	11.38	1.49
Afternoon (1336 IST)													
Depth 5 cm													
Mean	24.36	28.96	35.38	38.86	39.00	35.71	33.27	33.28	33.35	32.29	28.88	25.31	32.39
SD	1.82	1.86	1.92	2.29	2.13	1.75	0.84	1.44	1.45	1.08	1.01	2.17	0.81
CV (%)	7.47	6.43	5.43	5.90	5.47	4.89	2.53	4.33	4.35	3.33	3.49	8.58	2.50
Depth 15 cm													
Mean	20.18	24.04	29.82	33.68	34.57	32.94	30.90	30.76	30.87	32.22	28.79	25.21	29.50
SD	1.04	1.44	1.49	1.78	1.40	1.42	0.54	0.97	0.84	1.17	1.20	2.30	0.42
CV (%)	5.15	5.98	5.01	5.29	4.06	4.31	1.76	3.14	2.70	3.63	4.17	9.13	1.44
Depth 30 cm													
Mean	19.14	22.55	27.25	30.72	32.18	31.37	29.98	29.90	29.78	28.69	24.96	21.23	27.31
SD	1.01	0.89	1.17	2.28	1.00	1.12	0.53	1.00	0.59	0.73	0.75	2.01	0.40
CV (%)	5.29	3.95	4.30	7.43	3.12	3.56	1.76	3.36	2.00	2.56	3.01	9.45	1.48

R^2 values showed that the prediction of soil temperatures using mean air temperature could explain more than 99% variability of soil temperatures for all three depths in morning. While precision in prediction of soil temperatures in afternoon (1336 IST) increased when daily maximum air temperatures were used in an exponential model for 5 cm soil depth, and power model for 15 cm depth; however, for 30 cm depth daily mean air temperatures rather than maximum air temperature, were best fitted to the exponential model to predict soil temperatures in afternoon. The variability in predicted soil temperatures by the developed models could be explained more than 97% at 5 and 15 cm

soil depths, and 99% at 30 cm depth, which was evident by corresponding R^2 values of 0.978, 0.971 and 0.993. The lower and upper limits of confidence interval (at 95% level) of the predicted soil temperatures were computed statistically and presented in Fig. 4. Data showed that all the predicted soil temperature values were bounded within the limits of 95% confidence interval.

Prediction of weekly soil temperatures from weekly air temperature data was performed to understand the variability of soil temperatures, which is required for ecosystem management. Like daily data, regression analysis was carried out with average weekly air temperature, and soil

Table 4. Sen slope (Q) ($^{\circ}\text{C y}^{-1}$) and p value ($p = 0.05$) of Mann-Kendall test for monthly soil temperature at 0636 and 1336 IST for 5, 15, and 30 cm soil depths in study site over the period of 1985-2014

Month	Depth (cm)											
	5				15				30			
	0636 h		1336 h		0636 h		1336 h		0636 h		1336 h	
	Q	p value	Q	p value	Q	p value	Q	p value	Q	p value	Q	p-value
Jan	0.027	0.292	-0.103*	0.006	-0.033	0.205	-0.028	0.284	-0.024	0.309	-0.040*	0.018
Feb	0.006	0.803	-0.065	0.232	-0.033	0.326	-0.009	0.748	-0.002	0.886	-0.021	0.401
Mar	0.037	0.090	-0.031	0.344	-0.001	0.915	0.056	0.138	0.016	0.422	-0.014	0.544
Apr	0.038	0.143	0.019	0.775	0.010	0.858	0.040	0.276	0.046	0.164	0.053	0.129
May	0.060*	0.047	-0.018	0.816	0.010	0.748	0.087*	0.007	0.014	0.630	0.010	0.655
Jun	0.041*	0.027	0.016	0.580	0.018	0.486	0.036	0.164	0.020	0.353	0.013	0.412
Jul	0.034*	0.002	-0.010	0.668	0.018*	0.038	0.025*	0.039	0.017	0.186	0.009	0.442
Aug	0.037*	0.001	-0.011	0.695	0.008	0.497	0.029	0.083	0.010	0.284	0.014	0.292
Sep	0.036*	0.002	-0.007	0.695	0.014	0.116	0.018	0.174	0.000	0.929	-0.001	0.680
Oct	0.041*	0.046	-0.060*	0.032	0.000	0.957	-0.076*	0.014	0.003	0.844	0.000	0.957
Nov	0.047	0.134	-0.063*	0.005	-0.011	0.642	-0.078*	0.003	-0.014	0.531	-0.013	0.421
Dec	0.032	0.148	-0.105	< 0.001	-0.033	0.068	-0.123*	< 0.001	-0.014	0.432	-0.020	0.211

*significant at 5% level.

temperatures at 5, 15, and 30 cm depths in morning (0636 IST) and afternoon (1336 IST) (Fig. 5). In morning, highest R^2 values were found when mean air temperatures were correlated with soil temperatures at all three depths. Moreover, the power function models were best fitted at 5 cm ($R^2=0.994$) and 15 cm ($R^2=0.997$) soil depths, whereas the exponential model at 30 cm ($R^2=0.993$). But in afternoon, soil temperatures at 5, 15, and 30 cm depths were highly correlated with maximum air temperature by exponential model ($R^2=0.989$), mean temperature by power function model ($R^2=0.985$), and mean temperature by exponential model ($R^2=0.992$), respectively. For both the times, these models by using only air temperature could explain more than 99% variability in soil temperature at all three depths.

Monthly soil temperatures simulated from air temperature data are used as an input variable in many simulation models like CENTURY (Parton, 1996), RothC (Coleman and Jenkinson, 1996), and DNDC (Li, 1996). For site specific calibration and validation of these models, development of regression models is necessary. Toy *et al.* (1978) developed regression model to predict monthly soil temperature from monthly air temperature data, and suggested to develop such regional model at various depths for greater accuracy. The regression analysis was, therefore, performed by taking 30 years averaged monthly air temperature, and soil temperature data at 5, 15, and 30 cm soil depths

(Fig. 6). Similar to weekly regression analysis, monthly soil temperatures at all three depths in morning were highly correlated with mean air temperature, and power model was best fitted at 5 cm with R^2 of 0.996, exponential models at 15 and 30 cm depths with R^2 of 0.999 and 0.992, respectively. However, in afternoon, using maximum air temperature gave best fitted exponential model ($R^2=0.990$) at 5 cm, and logarithmic model ($R^2=0.901$) at 15 cm depth. But at 30 cm, using mean air temperature gave best fitted power model ($R^2=0.992$). For all the cases, the prediction models can explain more than 99% variability using average air temperature data except for 15 cm (~90%) in afternoon, which might be due to soil moisture content and the logarithmic relationship.

During night time the surface soil dissipated heat energy and in morning it became almost in equilibrium with air temperature (Parton and Logan, 1981), therefore, at 5 cm we obtained the best fitted power function model for daily data. But in afternoon the best fitted models were exponential because from sunrise to mid-day, it was observed that initially the rate of increase of air and surface soil temperature was slow, but thereafter it increased in a faster rate in silty loam soil (sand 26.04%, silt 56.16%, clay 7.80%). But at 15 cm depth in loam soil, (sand 42.04%, silt 36.08%, clay 21.88%) they were reverse in morning as well as in afternoon, which might be attributed to the slow upward

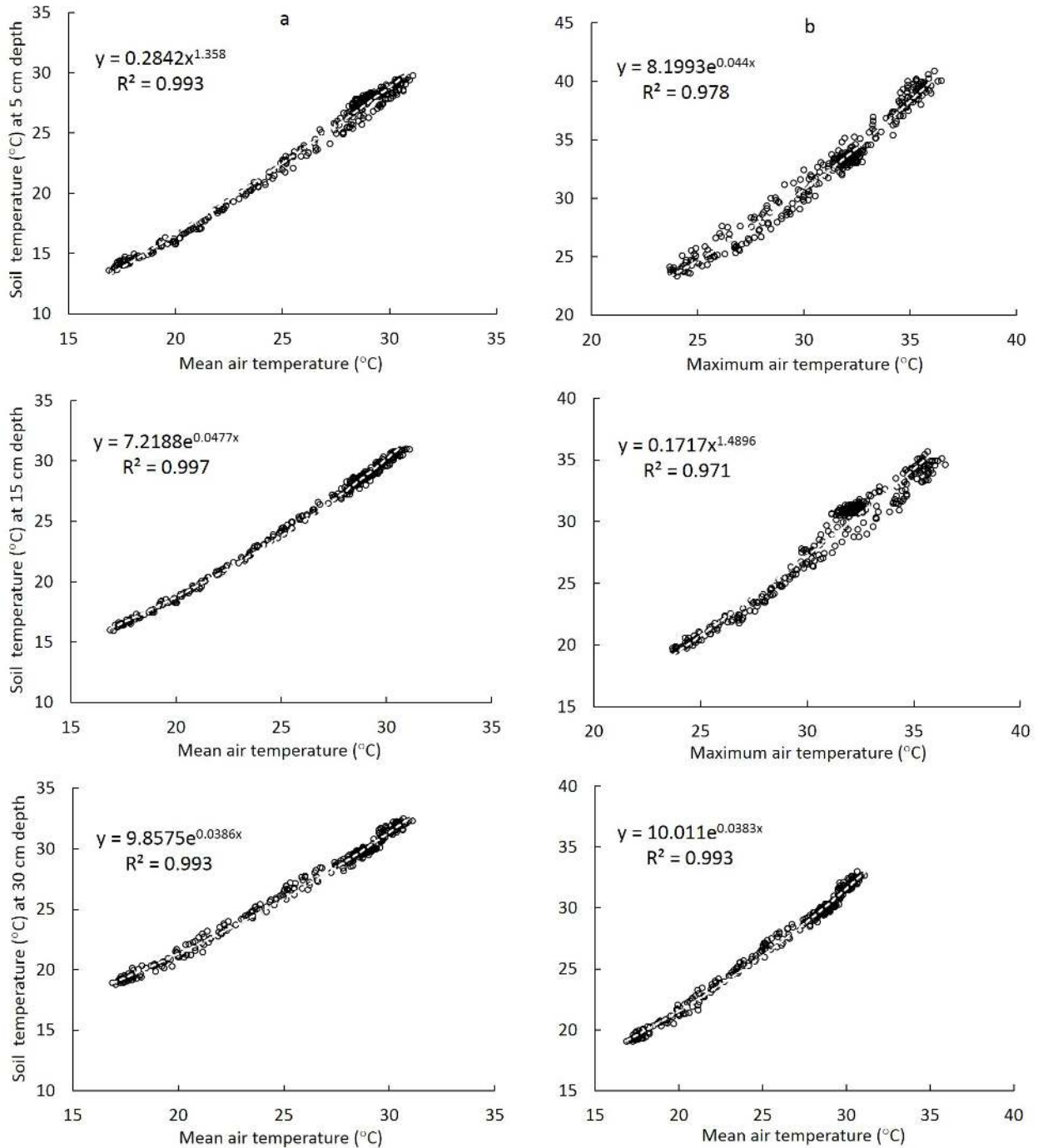


Fig. 3. Prediction of daily soil temperatures at 5, 15, and 30 cm depths in: a – morning and b – afternoon using daily air temperature data for alluvial soils in lower Indo-Gangetic plain.

heat transmission in the case of former due to the limited heat supply from lower soil layer but it was faster in latter due to constant heat supply chain from solar radiation to the adjacent surface soil layer. However, at 30 cm soil depth in sandy loam soil (sand 49.96%, silt 26.08%, clay 23.96%), exponential functions depicted the general decay of heat energy for upward and downward directions in morning and afternoon, respectively.

Recently surface soil temperature at unknown locations have been predicted by interpolating measured surface soil temperatures (Kang *et al.*, 2000; Liang *et al.*, 2013). But its relation with sub-soil temperature needs to be studied for better soil profile management in respect to crop growth. The empirical models, therefore, were developed by taking 30 years average daily soil temperatures at surface (5 cm) and sub-surface (15 and 30 cm) soils and presented in Fig. 7. Soil temperatures at 5 cm depth in morning

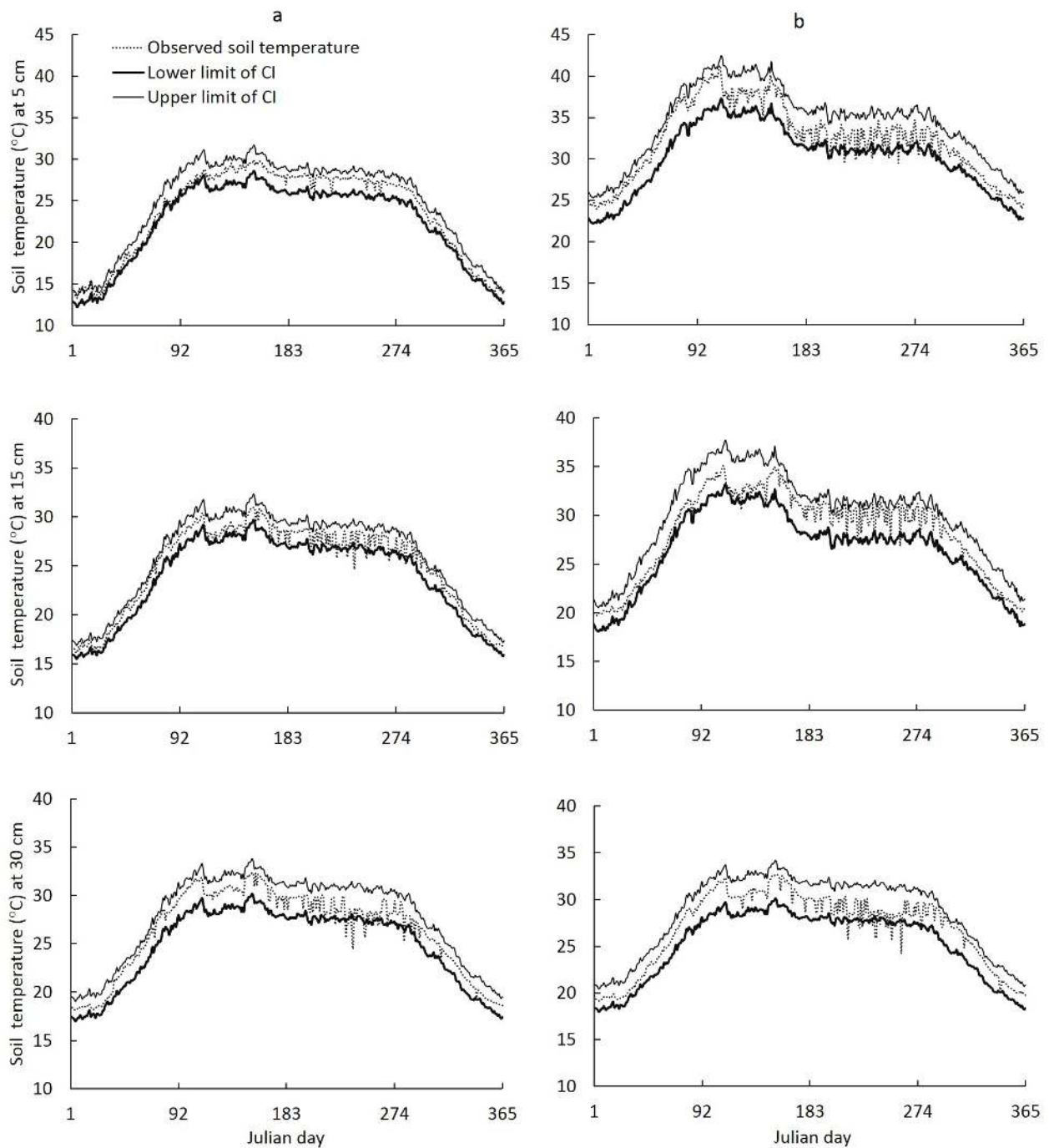


Fig. 4. Comparison between daily observed, and lower and upper limit of predicted soil temperature at 5, 15, and 30 cm soil depths in: a – morning (0636 IST) and b – afternoon (1336 IST) at 95% confidence interval (CI). Daily soil temperatures at all three depths were predicted using daily air temperature data.

was highly correlated at 15 and 30 cm soil depths having a power function relationship with R^2 values of 0.996 and 0.989, respectively. But in afternoon, logarithmic regression models showed better correlation between 5 cm, and 15 and 30 cm soil temperature data. In morning irrespective of soil factors like texture and moisture, temperature in soil profile became equilibrium, and therefore, power function

relationship was developed. However, surface soil due to its low clay (7.80%) and moisture content is heated faster by direct solar radiation and advection from hot wind in afternoon, but vertical conduction of heat from surface soil increased sub-soil temperature slowly due to comparatively higher clay (21.88% at 15 cm, and 23.96% at 30 cm) and moisture content in the subsequent layers. The influence of

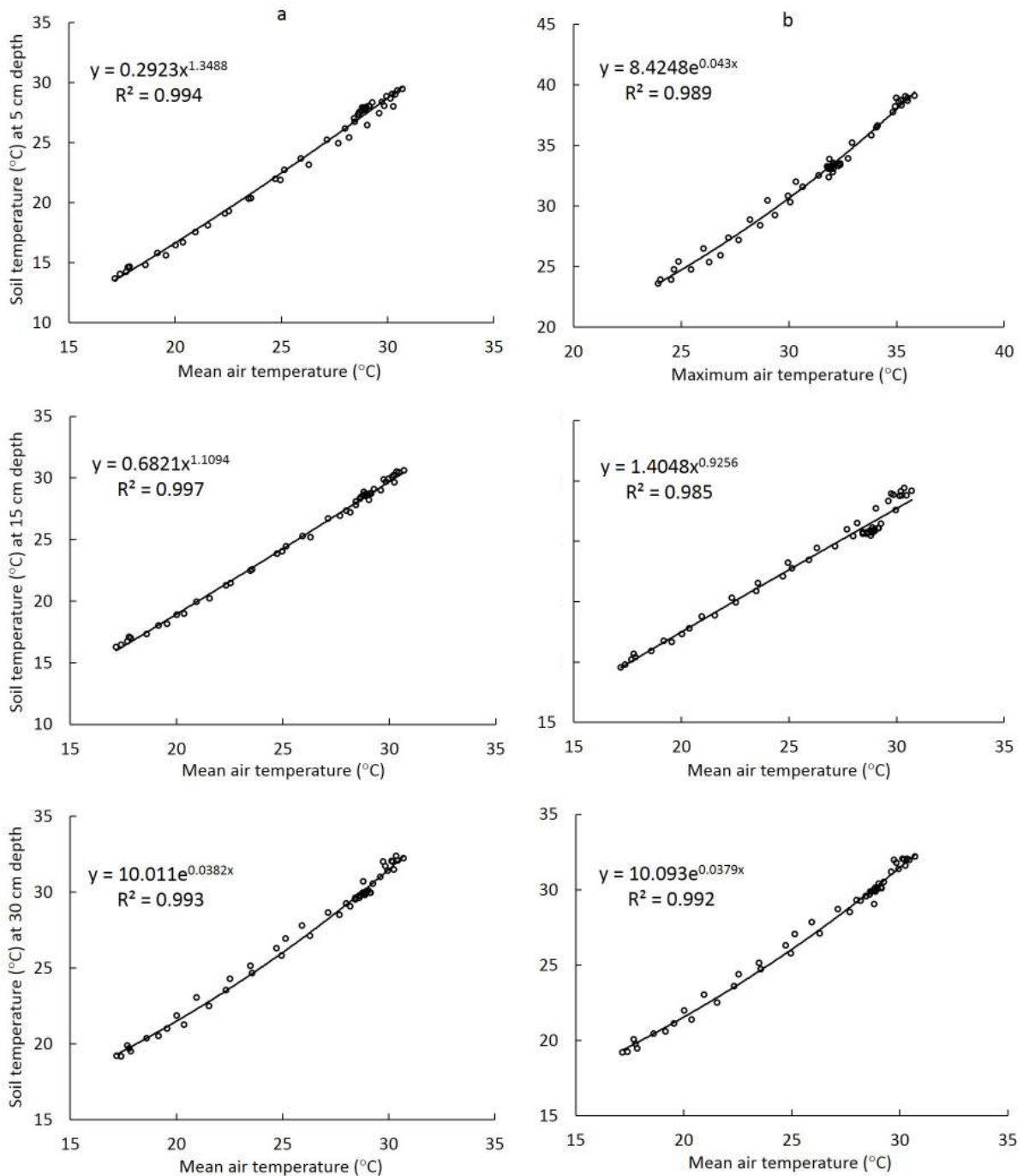


Fig. 5. Prediction of weekly soil temperatures at 5, 15, and 30 cm depths in: a – morning (0636 IST) and b – afternoon (1336 IST) using weekly air temperature data for alluvial soils in lower Indo-Gangetic.

these soil properties on thermal conduction and convection processes in soil was reported by Gao *et al.* (2003). This led to develop logarithmic relationship in afternoon. The lower and upper limits of confidence interval (at 95% level) of the predicted soil temperatures at 15 and 30 cm soil depths were computed and presented in Fig. 8. It was evident from the Fig. 8 that all the predicted soil temperature values were bounded within the limits of 95% confidence interval.

CONCLUSIONS

1. In general, temperature in alluvial soils increased with soil depth up to 30 cm in morning but the trend was reverse in afternoon. The long-term (1985-2014) average minimum and maximum temperatures at 5 cm depth were found higher than corresponding air temperatures.
2. Regression analysis revealed that daily, weekly, and monthly morning soil temperature up to 30 cm depth in alluvial soils could be predicted efficiently using

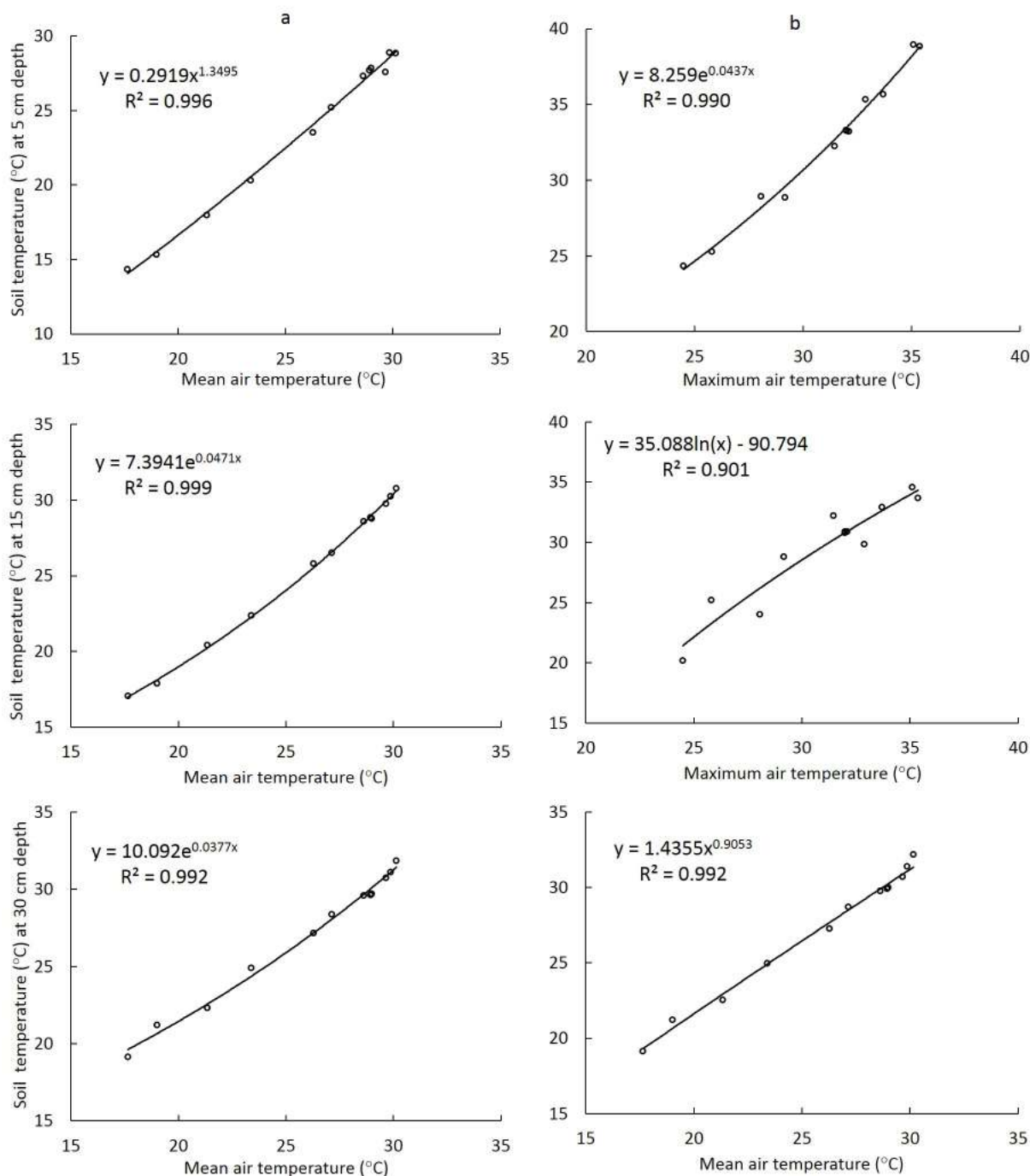


Fig. 6. Prediction of monthly soil temperatures at 5, 15 and 30 cm depths in: a – morning (0636 IST) and b – afternoon (1336 IST) using monthly air temperature data for alluvial soils in lower Indo-Gangetic plain.

corresponding mean air temperature. While using of maximum air temperature is suggested for afternoon soil temperature prediction up to 15 cm soil depth, beyond which (up to 30 cm) mean air temperature would give better prediction.

3. Empirical models were also developed to predict daily sub-soil temperature (at 15 and 30 cm depths) using long-term average daily surface soil temperature (at 5 cm). While air temperature data are scarce, these models could

be used to derive sub-soil temperature where surface soil temperatures are known or could be derived by methods like interpolation in spatial tools, viz. remote sensing and geographic information system (GIS).

4. Although the coefficients and constants were estimated for only one site, but considering the long-term data in this study, the general method/models of estimating soil temperature could be applicable to other sites in similar ecologies with little bit of site specific modification.

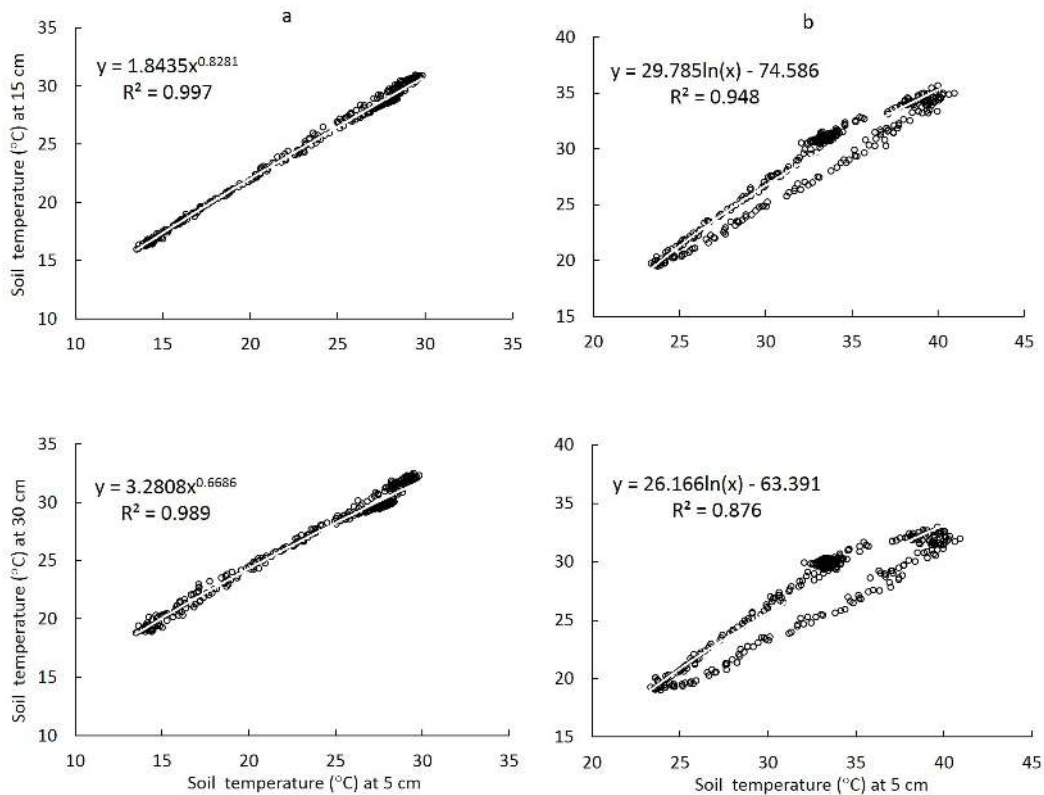


Fig. 7. Prediction of daily sub-soil temperature at 15 and 30 cm depths using surface soil temperature data at 5 cm in: a – morning (0636 IST) and b – afternoon (1336 IST) for alluvial soils in lower Indo-Gangetic plain.

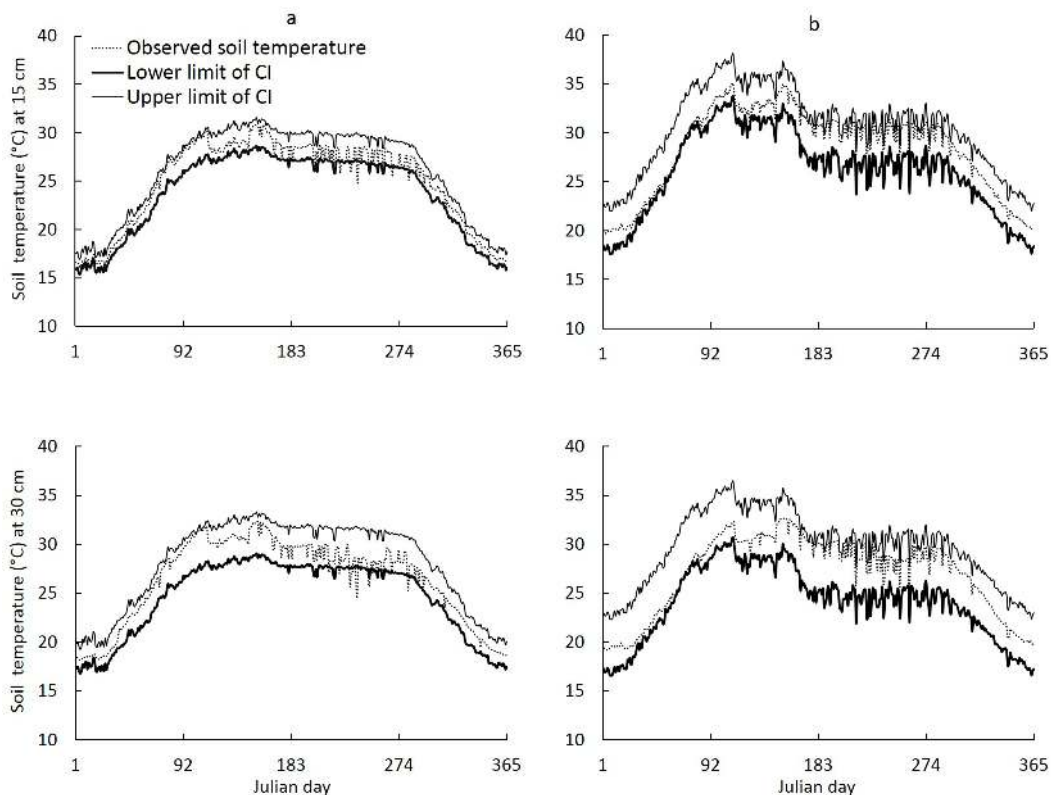


Fig. 8. Comparison between daily observed, and lower and upper limit of predicted soil temperature at 15 and 30 cm soil depths in: a – morning (0636 IST) and b – afternoon (1336 IST) at 95% confidence interval (CI). Daily soil temperatures at both the depths were predicted using surface soil temperature data at 5 cm.

5. These models after validation at multiple locations can be used to predict depth wise soil temperatures for various purposes, which has a greater implication in developing methodologies in space technology like remote sensing for upscaling or downscaling.

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