Estimation of solar radiation using two step method in West Bengal

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सार – भौतिक, रासायनिक और जैवीय अनेक प्रक्रियाओं के लिए सौर विकिरण ऊर्जा का मुख्य स्रोत है। मापित सौर विकिरण डाटा की अनुपलब्धता से अन्य मापित मौसम वैज्ञानिक परिवर्तनशीलता से सौर विकिरण का आकलन महत्वपूर्ण विकल्प प्रस्तुत करता है। इस शोध पत्र में हमने सामान्यत: प्रयोग होने वाले वायु तापमान पर आधारित मॉडलों को प्रमाणित किया और उनका मूल्यांकन किया। डमडम (गांगेय पश्चिमी बंगाल का स्टेशन) के मौसम के आँकड़ों का प्रेक्षण किया गया कि क्या यह इस क्षेत्र पर कार्यान्वित होगा या नहीं होगा। हमने उसी स्टेशन, जैसे कि डमडम (22.39 उ., 88.27 पू.) लोकल पॉवर-2 मॉडल (डिगी दो पॉलिनॉमियल सहित) को भी प्रमाणित किया और लोकल मॉडल (रैखीय प्रकृति की) की अपेक्षा अधिक अच्छे परिणाम दिखाए। हालांकि सामान्यत: दो चरणों में मापित वायु तापमान से सौर विकिरण का आकलन करने के लिए दो चरणीय पद्वति स्थान के सौर विकिरण का अधिक सटीक आकलन देते हैं। विभिन्न नियम त्रुटि का आकलन करते हुए मॉडल निष्पादन का आकलन किया गया हैं। इन परिणामों से यह पता चलता है कि दो चरणीय पद्वति अच्छा प्रदर्शन करती है और विशेष रूप से तापमान पर आधारित मॉडल अत्यधिक अच्छा प्रदर्शन करते हैं, जैसा कि हमसे पहले के शोधकर्ताओं ने भी बताया है। S/S_0 समीकरण के प्राचलों का आकलन बहु समाश्रयण मॉडल से किया गया और सौर विकिरण का आकलन करने के लिए दो चरणीय पद्वति का उपयोग किया गया। प्रस्तावित समीकरणों से निर्धारित प्राचलों का उपयोग करते हुए अच्छे प्रदर्शन का पता चलता है। इसीलिए प्रस्तावित समीकरणों से निर्धारित प्राचलों के साथ दो चरणीय पद्वति का उपयोग पश्चिम बंगाल और इस तरह की स्थलाकृति वाले भारत के विभिन्न भागों में भी सौर विकिरण के आकलन के लिए प्रयोग में लाई जा सकती है। ऐसा माना गया है कि ऐसे स्थान जहां मापित सौर विकिरण और धूप की अवधि के आँकड़े उपलब्ध नहीं हैं यह पद्वति उपयोगी सिद्ध होगी जबकि वायु तापमान को मापना सामान्य होता है।

ABSTRACT. Solar radiation is the main source of energy for many physical, chemical and biological process .Estimation of solar radiation from other measured meteorological variables offers an important alternative in the absence of availability of measured solar radiation data. In this paper, we validate and assess five commonly used air temperature based models. The weather data of Dumdum (a station in Gangetic West Bengal) has been taken to observe whether the same works for this region or not. We have also validated and assessed a Local power-2 model (polynomial with degree two) with the same station, *i.e.*, Dumdum (22.39° N, 88.27° E) and found it to give a more good result than Local model (linear in nature) so far developed. However the two step method to estimate solar radiation from the commonly measured air temperature in two steps gives more accurate estimation of solar radiation of a place. The model performance is evaluated using different law of error. Results show that the two step method gives good performance and significantly outperforms the temperature based models as claimed by our predecessors. The parameters of S/S_0 equation were calculated by multiple regression model and was used `in the two step method for calculating the solar radiation. It is found that the two step method using the parameters determined by the proposed equations gives good performance. Therefore the two step method with the parameters determined by the proposed equations could also be used to estimate solar radiation in West Bengal and also at different places in India having similar topography. It is believed to be useful for the site where no measured solar radiation and sunshine duration data is available, whereas the air temperature are commonly measured.

Key words – Solar radiation, Air temperature, Multiple regression model, Local power-2 model.

1. Introduction

Sun's energy is the main source of energy for many physical, chemical and biological processes, such as crop growth, plant photosynthesis. It is also essential and important variable to many simulation models studies, such as agriculture, environment, hydrology, meteorology and ecology. Hence, accurate records of solar radiation are of vital importance. However it is not widely available due to excessive cost and difficulties in maintenance and calibration of the measurement equipment (Hunt *et al*., 1998). Only small percent of the meteorological

stations of the countries are measuring this parameter. For example, in USA, less than 1% of meteorological stations are recording solar radiation (NCDC, 1995; Thorton and Running, 1999). In China, only 98 stations are recording solar radiation (Chen *et al*., 2004).Thus accurate methods have to be developed if possible space-wise for estimation of solar radiation so that relatively correct estimation of the solar radiation can be found out for use as input in different simulation model studies carried out in the neighbourhood of the station that is being studied.

India has about 300 clear, sunny days in a year, it's theoretically calculated solar energy incidence on it's land area alone is about 18000 trillion mega joules (MJ) per year , so to use this huge renewable source in all fields , it is doing an extensive study by setting up a large network of 45 radiation observatories to record   the   different components of solar radiation but the not recorded solar radiation data between stations can be filled by estimation of solar radiation by two step method.

A number of methods , including satellite - derived (Frulla *et al*., 1988; Pinker *et al*., 1995; Olseth and Skartveit, 2001), Stochastic algorithm (Richardson, 1981; Hansen, 1999; Wilks and Wilby, 1999) and Empirical relationships (Angstrom, 1924; Prescot, 1940), interpolation - based (Hay and Suckling, 1979; Rivington *et al*., 2006) Learning machine method (Tymvios *et al*., 2005; Lam *et al*., 2008; Chen *et al*., 2011) have been developed for this purpose. Among them, the empirical relationship method is attractive for its simplicity, efficiency and much lower data requirement. Angstrom (1924) first proposed a linear relationship between the ratio of average daily solar radiation to the corresponding value on a clear sky and the ratio of average daily sunshine duration to the maximum possible sunshine duration. Prescot (1940) modified this method by replacing the clear sky radiation with the extraterrestrial radiation .Based on the daily data of Pune, Das and Pujari (1993) developed a relationship between solar irradiance and the daily range of temperature and tested it for Hyderabad and Kolkata to get encouraging results. Subsequently, the well known sunshine based Angstrom-Prescot (A-P) model was developed. Despite its good performance even for West Bengal, as proved through the works of Lala (Roy) *et al*., 2013, it is often limited by the lack of sufficient sunshine duration records. To circumvent this difficulty, lots of air temperature based models have been developed and widely used (Hargreaves and Samani, 1982; Bristow and Campbell, 1984; Hargreaves *et al*., 1985; Chen *et al.*, 2004). These models allow widespread applications because air temperatures are routinely measured at most meteorological stations. However, a number of studies have shown that the sunshine based A-P model significantly outperformed the

temperature based models (Iziomon and Mayer, 2002; Podesta *et al*., 2004; Trnka *et al*., 2005) Therefore , more accurate solar radiation estimation using air temperature is of vital importance and significance.

The much better performance of the sunshine based A-P model over the temperature based model seems to indicate that if the sunshine duration could be estimated from air temperature, then the estimated sunshine duration could be used as inputs for A-P model to estimate solar radiation and the conversion in this way may be able to improve the estimation accuracy over the temperature - based models. This method was named by Chen *et al.* (2015), as two - step estimation method, this method estimates the sunshine duration using air temperature firstly, and then estimate solar radiation by A-P model using the estimated sunshine duration.

In the present work, five widely used air temperature - based models and a local regression model are studied. The main objectives of this study are to (1) calibrate and validate the temperature based models from data (2) investigate and evaluate the two step method.

2.   Data and methodology

2.1. *Site and data set*

The current study focuses on the site of Dumdum, where solar radiation measurements are taken and it lies in the alluvial plain of river Ganga and experiences tropical type of climate, this region is characterized by abundant water resource and thus plays significant role in water supply for agricultural production. Average annual rainfall for this region ranges from 1089.4 mm to 2446.8 mm and average annual bright sunshine hours for this region ranges from 1804.4 hrs to 2617.8 hrs. The mean daily solar radiation (MJ m^{-2}), sunshine duration (h), air temperature (°C), including mean maximum temperature and minimum temperature are used in this study. The data were obtained from NDC, Pune.

2.2. *Temperature based solar radiation estimation models*

2.2.1. *H-S model*

Hargreaves and Samani (1982) suggested a solar radiation estimation model that is a function of extraterrestrial radiation, maximum and minimum temperature as follows:

$$\frac{R_s}{R_a} = a\left(T_{\max} - T_{\min}\right)^{0.5} \qquad (1)$$

TABLE 1

The empirical parameters of the temperature-based models

Station	H-S model		H-Sm model			BC model				Chen model		
	Avg. a	R^2	a	b	R^2	a	Avg. b	c	R^2	a	b	R^2
Dumdum	0.153	0.71	0.14	0.039	0.71	0.7	0.009	2.4	0.69	0.17	-0.009	0.73

Station	Local model			Local power -2 model			
	a	b	R^2	a	b	c	R^2
Dumdum	0.022	0.253	0.684	-0.005	0.125	-0.027	0.798

TABLE 2

The empirical parameters of A-P model and local S model from SPSS

Station	A-P model			Local S model (from SPSS)			
	a	b	R^2	a	b	c	R^2
Dumdum	0.4247	0.2579	0.9359	0.0754	-0.0612	-0.5413	0.746

where, R_s is monthly mean daily actual global radiation (MJ m^{-2}), Tmax and Tmin are maximum and minimum temperature, respectively. R_a is mean daily extraterrestrial solar radiation (MJ m^{-2}), which is a function of latitude and day of the year. The detailed procedure for calculation of extraterrestrial radiation can be found in Allen *et al.* (1998), here 'a' is empirical parameter, which was recommended to be 0.16 for interior regions and 0.19 for coastal regions. This parameter has been verified by this author for the region under study in Lala (Roy) *et al.* (2013) and has been computed equal to 0.153 for this region.

2.2.2. *H-Sm model*

Hargreaves *et al.* (1985) further modified the H-S model by adding an empirical correction parameter and obtained the following equation:

$$\frac{R_s}{R_a} = a(T_{max} - T_{min})^{0.5} + b \tag{2}$$

where, *a* and *b* are empirical parameters.

2.2.3. *B-C model*

Bristow & Campbell (1984) studied the relationship between solar radiation and maximum, minimum temperature and developed the equation given below:

$$R_s = a\, R_a \left\{ 1 - \exp\left[-b(\Delta T_i)^c \right] \right\} \tag{3}$$

a, *b* and *c* are parameters, values widely used for these coefficients are 0.7 for a, 2.4 for *c* and the value of *b* can be calculated from the equation:

$$b = 0.036 \exp\left(-0.154 \Delta \overline{T}\right) \tag{4}$$

where, $\Delta \overline{T}$ is the monthly average of the $\Delta \overline{T_i}$ daily values, $\Delta \overline{T_i}$ is the air temperature difference calculated by subtracting the average T_{min} of the current and the next day from the T_{max} of the current day :

$$\Delta T_i = T_{max},i - \frac{T_{min},i + T_{min},i+1}{2} \tag{5}$$

where, T_{max},i , T_{min},i, $T_{min},i+1$ are T_{max}, T_{min}, in ith day, T_{min} in (i+1)th day, respectively.

2.2.4. *Chen model*

Chen *et al.* (2004) presented a new model as follows:

$$\frac{R_s}{R_a} = a \ln(T_{max} - T_{min}) + b \tag{6}$$

where, a and b are empirical parameters.

2.2.5. *Local model*

In addition to these well known models, Chen proposed the following equation based on his

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TABLE 3

Root mean square error (RMSE in MJ m⁻²) , Relative root mean square error (RRMSE), Mean absolute bias error (MABE in MJ m⁻²) and mean absolute percentage error (MAPE) of the temperature based models

Station: Dumdum (Kolkata Airport)	H-S Model				H-Sm Model			
Year	RMSE	RRMSE	MABE	MAPE	RMSE	RRMSE	MABE	MAPE
2007	3.466088	22.97715	2.546046	28.93079	3.749019	24.85274	2.874582	31.820886
2008	4.147926	28.18477	2.945165	35.77673	4.30001	29.21817	3.109136	37.832369
2009	3.925267	27.11447	2.976165	28.23522	3.901909	26.95312	2.964177	29.226787
2010	3.827083	22.87831	2.633082	15.02331	4.264941	25.49582	3.098713	17.992606
2011	3.368293	19.53482	2.362109	14.05536	3.352263	19.44186	2.521674	14.987449
Mean	3.746931	24.1379	2.692513	24.40428	3.913628	25.19234	2.913656	26.37202
Std. Dev.	0.324524	3.512812	0.263838	9.481571	0.392134	3.62571	0.239889	9.604719

Station: Dumdum (Kolkata Airport)	B-C Model				Chen Model			
Year	RMSE	RRMSE	MABE	MAPE	RMSE	RRMSE	MABE	MAPE
2007	5.963616	39.53359	4.843022	45.78977	4.817594	31.93646	4.006249	31.60256
2008	6.852554	46.56247	5.370144	56.97154	4.666284	31.70697	3.87975	33.89092
2009	6.978642	48.2062	5.936184	51.96764	3.975538	27.46173	3.189569	24.32826
2010	5.455692	32.61414	4.735609	29.96766	6.218966	37.17699	4.780566	25.8195
2011	4.76059	27.60962	3.882695	24.5471	5.897253	34.20183	5.21331	29.71076
Mean	6.002219	38.9052	4.953531	41.84874	5.115127	32.4968	4.213889	29.0704
Std. Dev.	0.937856	8.841731	0.765762	14.02792	0.924504	3.57425	0.794349	3.972265

Station: Dumdum (Kolkata Airport)	Local Model				Local Power Model			
Year	RMSE	RRMSE	MABE	MAPE	RMSE	RRMSE	MABE	MAPE
2007	3.807178	25.23828	2.929542	33.10228	2.973662	20.34192	1.963815	24.32686
2008	4.361014	29.63269	3.158544	38.67852	3.161558	22.2774	1.99407	29.05156
2009	3.961175	27.36251	3.021083	29.97669	3.032898	21.85795	1.963557	22.20902
2010	4.264915	25.49567	3.100121	18.13266	3.483483	20.80227	2.23936	12.66026
2011	3.279753	19.02132	2.467563	14.60902	3.191594	18.30965	2.004419	12.15558
Mean	3.934807	25.35009	2.935371	26.89983	3.168639	20.71784	2.033044	20.08066
Std. Dev.	0.429157	3.952136	0.275306	10.18089	0.197576	1.555627	0.116754	7.43146

investigation of relationship between R_s/R_a & maximum, minimum temp. (hereafter referred to local R_s model).

$$\frac{R_s}{R_a} = a\left(T_{max} - T_{min}\right) + b \qquad (7)$$

where, a and b are empirical parameters.

2.2.6. *Local power-2 model*

Also, these authors proposed the following equation based on the investigation of relationship between R_s/R_a and maximum, minimum temperature in this local conditions (hereafter referred to local power-2 model).

$$\frac{R_s}{R_a} = a\left(T_{max} - T_{min}\right)^2 + b\left(T_{max} - T_{min}\right) + c \qquad (8)$$

where *a*, *b* and *c* are empirical parameters.

The values of all the parameters of the above temperature based models and the value of coefficient of regression (R^2) computed between R_s/R_a and difference of $T_{max} - T_{min}$, has been given in Table 1.

2.3. *Sunshine - based A-P model*

A-P model was proposed by Angstrom (1924) and further modified by Prescott (1940). The original form of this model is:

$$\frac{R_s}{R_a} = a\frac{S}{S_o} + b \qquad (9)$$

where, *a* and *b* are empirical parameters which are calibrated from regression analysis between S/S_o and R_s/R_a. S is mean daily actual duration of sunshine hours (h). S_o is mean daily maximum possible sunshine duration
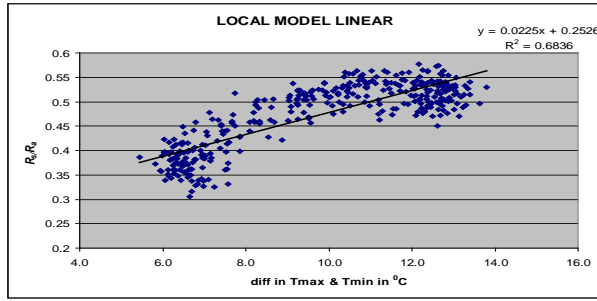
Fig. 1. Graph of Rs/Ra versus difference in Tmax & Tmin in Local model linear
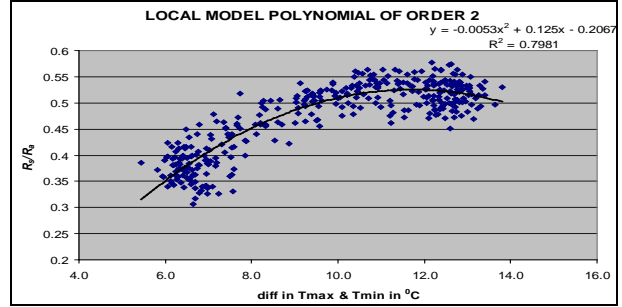

Fig. 2. Graph of Rs/Ra versus difference in Tmax & Tmin in Local model polynomial of order 2

(h_0) which is calculated using the equations detailed by Allen *et al.* (1998).

2.4. *Sunshine duration estimation model*

The formula to estimate mean daily sunshine duration using maximum and minimum temperature was formulated by Chen *et al.* (2011) as follows:

$$\frac{R}{R_o} = aT_{max} + bT_{min} + c \tag{10}$$

where, *a*, *b* and *c* are empirical parameters and whose values have been computed by multiple regression of daily mean of 26 years (*i.e*, 1980 to 2006) of maximum temperaure, minimum temperature and S/S_o. The values of all the parameters and the value of coefficient of regression (R^2) computed between R_s/R_a and S/S_o of the sunshine A-P model and the values of all the parameters and the value of coefficient of multiple regression (R^2) computed between S/S_o and T_{max} and T_{min} of the sunshine duration estimation model, has been given in Table 2.

2.5. *Performance criteria*

To assess the performance of models, root mean square error (RMSE), relative root mean square error (RRMSE) (%), mean absolute bias error (MABE) and mean absolute percentage error (MAPE) (%) has been found. The four indicators are calculated by the following equations:

$$RMSE = \sqrt{\frac{\sum_{i-1}^{n}(yi - \overline{y}i)^2}{n}} \tag{11}$$

$$RRMSE = \frac{100}{y}\sqrt{\frac{\sum_{i-1}^{n}(yi - \overline{y}i)^2}{n}} \tag{12}$$

$$MABE = \frac{1}{n}\sum_{i-1}^{n}| yi - \overline{y}i | \tag{13}$$

$$MAPE = \frac{100}{n}\sum_{i-1}^{n}\frac{| yi - \overline{y}i |}{| yi |} \tag{14}$$

where, *n*, *y*, *ẏ* and $\overline{y}$ represent the number of testing data, the observed value, the estimated value and the average value of the observation, respectively. Lower values of RMSE, RRMSE, MABE and MAPE indicate a better estimation accuracy of the model. The relative improvement of RMSE (RIrmse) and MABE (RImabe) were used to measure the improvement of the evaluated model accuracy over the reference model accuracy.

$$RIrmse = \frac{RMSE_r - RMSE_e}{RMSE_r} \tag{15}$$

$$RImabe = \frac{MABE_r - MABE_e}{MABE_r} \tag{16}$$

where, $RMSE_r$ and $MABE_r$ are the root mean square error and mean absolute bias error for the reference model, respectively. $RMSE_e$ and $MABE_e$ are the root mean square error and mean absolute bias error for the evaluated model, respectively. Higher values of RIrmse and RImabe indicate a better improvement over the reference model.

3. Results and discussion

3.1. *Performance of the temperature based models*

The performances of the six temperature based models are presented in Table 3. The H-S model, H-Sm model, BC model, Chen model (2004), Local model and Local power-2 models for the station from the year 2007 to 2011 has values of RMSE (averaged 3.747, 3.914, 6.002, 5.115, 3.935 & 3.169 MJ m^{-2}, respectively),

TABLE 4

Root mean square error (RMSE in MJ m^{-2}) , Relative root mean square error (RRMSE), Mean absolute bias error (MABE in MJ m^{-2}) and mean absolute percentage error (MAPE) of AP two step method

Station: Dumdum (Kolkata Airport)	AP two step method Model			
Year	RMSE	RRMSE	MABE	MAPE
2007	2.464173	12.96446	1.661259	18.32252
2008	2.32529	17.33904	1.46861	15.52661
2009	2.549712	19.05863	1.742915	15.25118
2010	2.89181	13.04524	1.309433	17.35703
2011	2.44455	16.37406	1.101425	16.38325
Mean	2.535107	15.75629	1.456728	16.56812
Std. Dev.	0.214887	2.689623	0.260679	1.279996

Fig. 3. Graph of daily mean of Rs/Ra versus daily mean of S/So

RRMSE (averaged 24.138%, 25.192%, 38.905%, 32.497%, 25.35% & 20.718% respectively), MABE (averaged 2.693, 2.914, 4.954, 4.214, 2.935 & 2.033 MJ m^{-2} respectively) and MAPE (averaged 24.404%, 26.372%, 41.849, 29.07, 26.9% & 20.081% respectively). These six models have similar equation expressions, they differ in the form of the term $T_{\max} - T_{\min}$, namely, the square root of $(T_{\max} - T_{\min})$ for H-S and H-Sm model, exponential of monthly average of $\left(T_{\max}, i - \dfrac{T_{\min}, i + T_{\min}, i+1}{2}\right)$ for BC model , natural log of $(T_{\max} - T_{\min})$ for Chen model, $(T_{\max} - T_{\min})$ for Local model and quadratic equation of $(T_{\max} - T_{\min})$ for Local power-2 model. Out of these average values validated from the year 2007 to 2011 the performances was better for Local power-2 model according to the indicators of RMSE, RRMSE, MABE and MAPE, indicating that the newly formulated model (*i.e*., Local power-2 model) will give better performances over Chen's local model in the temperature based model of evaluating R_s as can be seen from the Figs. 1&2.

3.2. *Performance of the two step method*

Despite the simplicity and significant performances of A-P model, it is often limited by the lack of available sunshine duration records. Therefore, in the present work, an attempt has been made to estimate sunshine duration by local S model [Eqn. (10)] using air temperature for the station. Consequently, the estimated sunshine duration is used as input for A-P model to estimate solar radiation, and the performance is presented in Table 4. This is a two step method as named by Chen *et al.* (2015). Such a method has not been studied before, for this region, which may be contributed to the lack of study on the relationship
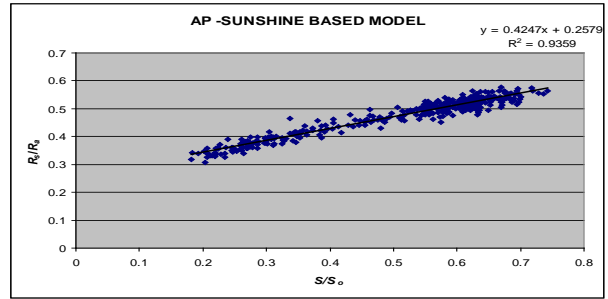
between the air temperature and the sunshine duration. Another reason may be that there are two estimation processes which may largely decrease the performance accuracy. However in the present work, the two step method gives good performances with the RMSE < 3 MJ m^{-2} for the validation year 2007 to 2011 (averaged 2.535 MJ m^{-2}), RRMSE < 20% (averaged 15.756%), MABE < 2 MJ m^{-2} (averaged 1.457 MJ m^{-2}), and MAPE < 20% (averaged 16.568%) as shown in Table 4. Therefore, it could be used to estimate solar radiation in the Gangetic West Bengal area.

3.3. *Comparison of the two step method between temperature based models*

Performance comparisons of the two step method and temperature based models given in Tables 3&4 shows that the two step method gives the averaged RMSE of 2.535 ± 0.215 MJ m^{-2}, RRMSE of 15.756% ± 2.69%, MABE of 1.457 ± 0.261 MJ m^{-2} and MAPE of 16.568% ± 1.28% within the same station. The results of studies on relative improvement of the two step method over the temperature based models are presented in Table 5. Evidently, the two step method significantly out performs the temperature based models with the averaged RIrmse of five years (*i.e*., 2007-2011) -0.486, -0.549, -1.388, -1.017, -0.558 & -0.253; RImabe of -0.880, -1.041, -2.424, -2.053, -1.051 & -0.439 for H-S, H-Sm, B-C, Chen, Local and Local power-2 model, respectively. These results further confirm that the two - step method can significantly improve the estimation accuracy over the temperature - based models which directly estimate solar radiation using air temperature only. Also it confirms that Local power-2 model for R_s gives better performance than Local model and the two step method is the best estimator of R_s compared to the six temperatures based models.

3.4. *Determination of model parameters*

The two step method has substantial potential for application in solar radiation estimation due to greater availability of air temperature data and the significant performance, but the equation for determining constants

TABLE 5

The relative improvement of Root mean square error (RIrmse) and mean absolute bias error (RImabe) of the two step method over the temperature based models

Year	HS model		HSm model		BC model		Chen model		Local model		Local power model	
	RIrmse	RImabe	RIrmse	RImabe	RIrmse	RImabe	RIrmse	RImabe	RIrmse	RImabe	RIrmse	RImabe
2007	-0.407	-0.533	-0.521	-0.730	-1.420	-1.915	-0.955	-1.412	-0.545	-0.763	-0.207	-0.182
2008	-0.784	-1.005	-0.849	-1.117	-1.947	-2.657	-1.007	-1.642	-0.875	-1.151	-0.360	-0.358
2009	-0.539	-0.708	-0.530	-0.701	-1.737	-2.406	-0.559	-0.830	-0.554	-0.733	-0.190	-0.127
2010	-0.323	-1.011	-0.475	-1.366	-0.887	-2.617	-1.151	-2.651	-0.475	-1.368	-0.205	-0.710
2011	-0.378	-1.145	-0.371	-1.289	-0.947	-2.525	-1.412	-3.733	-0.342	-1.240	-0.306	-0.820
Mean	-0.486	-0.880	-0.549	-1.041	-1.388	-2.424	-1.017	-2.053	-0.558	-1.051	-0.253	-0.439

of the equation of local S model as given by Chen was giving faulty values for this region so it was evaluated by the multiple regression method from the available long term data (26 years) of the station to suit to local conditions and subsequently it gave better results. Hence, here we have brought a little modification to the local S model as given by Chen *et al.* (2015) by changing the value of it's parameters and showed this model equation will give better estimation of the solar radiation by using two step method for this region. We recommend to find the constant values of the local S model by running multiple regression method of the daily mean of maximum temperature, minimum temperature and S/S_0 for the year from the minimum 25 years previous station data to get better results by two step method.

3.5. *Solar radiation estimation using the estimated parameters*

The local S model with has been used to estimate S/S_0, which is later used as input to estimate solar radiation by A-P model using the parameter. Good performance of the two step method is found with the RMSE < 2.6 MJm^{-2} (averaged 2.54 MJm^{-2}) RRMSE < 20% (averaged 15.76 %), MABE < 1.5 MJ m^{-2} (averaged 1.46 MJ m^{-2}), MAPE < 20 % (averaged 16.57%) and R^2 > 0.9 (averaged 0.936) and there is a substantially good agreement between the daily mean of R_s/R_a with daily mean of S/S_0 as shown in Fig. 3 and the parameters generated from this relationship can be used to calculate the R_s of this area by the two step method.

4. Conclusions

Solar radiation is an essential and important variable for use in many simulation models. Plant growth is a direct function of solar radiation. Many transpiration models in plant - water relationship require solar irradiance as an input. Estimation of solar radiation from other commonly measured meteorological variables is generally done when direct measurement are not readily available. In this work, we present the two step method to estimate solar radiation for this region from the commonly measured air temperature, namely, estimate sunshine duration by local S model, using air temperature firstly and then the estimated sunshine duration is used as inputs for A-P model to estimate solar radiation. The model performance indicators of RMSE, RRMSE, MABE and MAPE illustrate that the two step method gives good results. Further comparisons show that the two step method significantly outperforms the temperature based models. Therefore, it could be used to estimate solar radiation in Gangetic West Bengal and it can significantly improve the estimation accuracy over the temperature based models which directly estimate solar radiation using air temperature only.

As we have already mentioned that the two step method has substantial potential for direct application in solar radiation estimation due to greater availability of air temperature data and it significant improved performance over the temperature based models. The two step method using the estimated parameters was used to validate the value of R_s from 2007-2011 and it is found that the estimated values agree well with the measured solar radiation. Therefore, the two step method with parameters determined by the equations as proposed in the paper could be used in Gangetic West Bengal and it is believed to be particularly useful for the sites where no solar radiation and sunshine duration data is available, whereas the air temperatures are commonly measured.

References

Allen, R. G., Pereira, L. S., Raes, D. and Smith, M., 1998, "Crop evapotranspiration", *Guidelines for computing crop water requirements*, FAO Irrigation and Drainage paper, p56, Rome.

Angstrom, A., 1924, "Solar and terrestrial radiation", *Quarterly Journal of the Royal Meteorological Society*, **50**, 121-126.

Bristow, K. L. and Campbell, G. S., 1984, "On the relationship between incoming solar radiation and daily maximum and minimum temperature", *Agriculture and Forecast Meteorology*, **31**, 159-166.

Chen, R. S., Ersi, K., Yang, J. P., Lu, S. H. and Zhao,W. Z.,2004, "Validation of five global radiation models with measured daily data in China", *Energy, Conversion and Management*, **45**, 1759-1769.

Chen , J.L .,Liu , H.B., Wu,W. And Xie,D.T.,2011, „Estimation of monthly solar radiation from measured temperatures using support vector machines- A case study " , Renewable Energy , 36,413-420.

Chen , J. L., Xiao, B. B., Chen, C. D., Wen, Z. F., Jiang, Y., Lv , M. Q., Wu, S. J. and Li G.S., 2015, "Estimation of solar radiation using two step method in Yangtze River basin in China", *Mausam*, **66**, 225-236.

Das, H. P. and Pujari, A. D., 1993, "A simple approach towards estimating solar irradiance", Mausam, **44**, 3, 239-242.

Frulla, L. A., Gagliardini, D. A., Grossi, G. H., Lopardo, R. and Tarplay, J. D., 1988, "Incident solar radiation on Argentina from the geostationary satellite GOES : Comparison with ground measurements", *Solar Energy*, **41**, 61-69.

Hansen, J. W., 1999, "Stochastic daily solar irradiance for biological modeling applications", *Agricultural and Forest Meteorology*, **94**, 53-63.

Hargreaves, G. H. and Samani, Z. A., 1982, "Estimating potential evapotranspiration", *Journal of Irrigation and Drainage Engineering*, **108**, 225-230.

Hargreaves, G. L., Hargreaves, G. H. and Riley, J. P, 1985, "Irrigation water requirement for Seegal River Basin", *Journal of Irrigation and Drainage Engineering*, **111**, 265-275.

Hay, J. E. and Suckling, P. W., 1979, "An assessment of the networks for measuring and modeling solar radiation in British Columbia and adjacent areas of Western Canada", *Canadian Geographic*, **23**, 222-238.

Hunt, L. A., Kuchar, L. and Swarztoa, C. J., 1998, "Estimation of Solar radiation for use in crop modeling", *Agricultural and Forest Meteorology*, **91**, 293-300.

Iziomon, M. G. and Mayer, H., 2002, "Assessment of some global solar radiation parameterizations", *Journal of Atmospheric and Solar Terrestrial Physics*, **64**, 1631-1643.

Lala (Roy), S., Bandyopadhyay, S. and Das, S., 2013, "Prediction of Maximum or Minimum air temperature in a coastal location in West Bengal", *Mausam*, **64**, 671-680.

Lam, J. C., Wan, K. K. W. and Yang, L., 2008, "Solar radiation modeling using ANNs for different climates in China", *Energy Conversion and Management*, **49**, 1080-1090.

NCDC (National Climatic Data Centre), 1995, "Cooperative summary of the day, dataset TD 3200", U. S. Department of Commerce, National Oceanographic and Atmospheric Administration, National Climatic Data Centre, Asbevilla, NC.

Olseth, A. and Skarrveit, A., 2001, "Solar irradiance sunshine duration and daylight illuminance derived from METEOSAT data for some European sites", *Theoretical and Applied Climatology*, **69**, 239-252.

Pinker, R. T, Frouin, R. and Li, Z., 1995, "A review of satellite methods to derive shortwave irradiance", *Remote Sensing of Environment*, **51**, 108-124.

Podesta, G. P., Nunez, L., Villanuava, C. A. and Skansi, M. A., 2004, "Estimating daily solar radiation in the Argentine Pampas", Agricultural and Forest Meteorology, **123**, 41-53.

Prescott, J. A., 1940, "Evaporation from a water surface in relation to solar radiation", *Transactions of the Royal Society of South Australia*, **64**, 114-118.

Richardson, C. W., 1981, "Stochastic simulation of daily precipitation, temperature and solar radiation", *Water Resources Research*, **17**, 182-190.

Rivington, M., Matthews, K. B., Bellocchi, G. and Buchan, K., 2006, "Evaluating uncertainty introducedto process-based simulation model estimates by alternative sources of meteorological data", *Agricultural Systems*, **88**, 451-471.

Thorton, P. E. and Running, S. W., 1999, "An improved algorithm for estimating daily solar radiation from measurements of temperature, humidity and precipitation", *Agricultural and Forest Meteorology*, **93**, 211-228.

Trnka, M., Zalud, Z., Eitzinger, J. and Dubrovský, M., 2005, "Global solar radiation in Central European lowlands estimated by various empirical formulae", *Agricultural and Forest Meteorology*, **131**, 54-76.

Tymvios, F. S., Jacovides, C. P., Michaelides, S. C. and Scouteli, C., 2005, "Comparative study of Ångström's and artificial neural network's methodologies in estimating global solar radiation", *Solar Energy*, **78**, 752-762.

Wilks, D. S. and Wilby, R. L., 1999, "The weather generation game: A review of stochasticweather models", *Progress in Physical Geography*, **23**, 329-357.