A Generalized Model for Global Solar Radiation in South Africa Using Multiple Weather Elements as Predictors

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ABSTRACT

In this study a generalized model for predicting Global Solar Radiation (GSR) was developed for South Africa. This was achieved by employing easily measured weather elements like sunshine hour, ambient temperature, relative humidity and wind speed as predictors. The model accuracy was verified by comparing estimated values with measured values of GSR in each province in terms of the following statistical error tests: mean bias error, mean absolute bias error, and mean absolute percentage error, root mean square error, and regression coefficient. The values of regression coefficient obtained for each location shows that the developed model is sufficed for use to predict GSR and hence, could be used for any location within the country.

Keywords: model, solar radiation, South Africa, predictors, weather elements

1. INTRODUCTION

In solar technology systems, the importance of GSR data cannot be overemphasized. The best way to obtain these data is by measuring it in situ and over a long term. However, constraints such as cost of procurement, maintenance, cost of recalibration or institutional constraints do hamper the availability and accessibility to these data, and where available, the data might be incomplete. For these reasons, there arises the need to develop models which use readily available weather elements as parameters to predict GSR.

Several works have been done in this aspect of modeling GSR with different methods being used to formulate these models. One of the earliest known solar radiation models was developed by Angstrom in 1924 [1] and was modified by Prescott [2] in 1940. The Angstrom-Prescott model expresses the ratio of the GSR to the extraterrestrial radiation on horizontal surface in terms of the sunshine hour in a linear form (Eq. 1)

$$\frac{\overline{H}}{\overline{H}_o} = a + b\frac{S}{S_0} \qquad (1)$$

Where '*a*' and '*b*' are the location-dependent, empirically determined regression coefficients and S/S_0, is the cloud clearness index. The extraterrestrial radiation is as expressed by Eq. 2 [3].

$$\overline{H}_0 = \frac{24\times 3600 G_{sc}}{\pi}\left(1+0.033\cos\frac{360 n_d}{365}\right) \times\left(\cos\phi\cos\delta\cos\omega_s + \frac{\pi\omega_s}{180}\sin\phi\sin\delta\right) \qquad (2)$$

In recent times, researchers have developed various models to predict GSR. Mellit *et al* [4] employed neural networks method to develop simplified model for generating sequences of GSR data for isolated sites. It was reported that the model produced prediction with Root Mean Square (RMSE) not exceeding 8% and a regression coefficient (R^2) between 90% and 92%. Menges *et al* [5] employed a combination of parameters like solar declination, extraterrestrial radiation, temperature, and evapotranspiration to develop a model for evaluation of radiation over Konya in Turkey. It was reported that the model has RMSE of 0.022576 MJ/m^2 and regression coefficient of 0.999993. In a study, Rivington *et al* [6] used fuzzy logic method to evaluate two air temperature based models and one sunshine duration based-model of solar radiation in 24 UK stations and reported that the sunshine hour based model gave the best estimate but with some systematic seasonal error and that only air temperature based models can also be used where air temperature is the only available data. Statistical methods have been used to formulate models for solar radiation, and to measure the correlation between radiation and other weather elements. In their study, Liu *et al* [7] evaluated 16 temperature-based GSR models across a wide range agro-ecological condition in China. They concluded that the availability of radiation is based on the difference in maximum and minimum ambient temperature and not on the average day temperature. They further reported that in the absence of sunshine hour data, temperature-based model can be used to predict GSR although with some error. In a

related study, Ibrahim *et al* [8] investigated the relationship between solar radiation and ambient air temperature over Northern Malaysia and reported that there is a strong correlation (coefficient 0.743) between solar radiation and temperature with coefficient of determination $R^2 = 0.5585$.

Validation of models is usually done by comparing predictions as obtained from the model to the measured solar radiation data. Wu *et al* [9] compared the accuracy of sunshine only based model to that of sunshine-temperature and temperature only based models and concluded that the most accurate prediction is made by sunshine-temperature based model, followed by the sunshine based model while the temperature based model gives the least accurate predictions.

Many of the developed models employ single predictor as model parameter while only a few considered using multiple predictors. Furthermore, most of these models use sunshine hour for this purpose [10, 11]. Therefore, the objective of this work is to develop a generalized model to predict GSR for South Africa by employing the monthly daily average sunshine hours, relative humidity, monthly daily average ambient temperature and wind speed as parameters.

2. DATA AND METHODOLOGY

2.1. Radiation and meteorological data

An eleven year data, which include monthly average radiation H, sunshine hour S, relative humidity ϕ, ambient temperature and wind speed c_w were obtained from Agriculture Research Council (ARC), South Africa and South Africa Weather Service (SAWS) for the different provinces in the country. Table 1 gives a summary of the station location and the period over which the analyzed data were collected.

No.	Station	Province	Lat. (°S)	Long. (°E)	Alt. (m)	Period of observation
1	Pietermaritzburg, Indlovu DC	Kwazulu-Natal	29.67	30.41	812	2001 – 2011
2	Pieterburg, Polokwane	Limpopo	23.73	29.60	1153	2001 – 2011
3	Nelspruit	Mpumalanga	25.45	30.97	674	2001 – 2011
4	Roodeplaat, Pretoria	Gauteng	25.60	28.35	1168	2001 – 2011
5	Lichtenburg	North West	25.99	26.50	1534	2001 – 2011
6	Waterford, Stellenbosch	Western Cape	34.00	18.86	259	2001 – 2011
7	Upington	Northern Cape	28.46	21.21	803	2001 – 2011
8	Dohne, Stutterheim	Eastern Cape	32.53	27.46	907	2001 – 2011
9	Glen, Bloemfontein	Free State	28.93	26.33	1232	2001 – 2011

Table 1: Station, province, geographical locations and period of data collection (Source: ARC, 2012)

The data supplied by ARC do not include the monthly average sunshine hour, hence, sunshine hours obtained from SAWS were used and it was ensured that the data used are those for locations with greatest proximity.

2.2. Selection of Predictors

A 2-tailed correlation test is run on every predictor and any predictor whose correlation was not significant at 0.001 was dropped from the model and was not used as formulation parameter. Table 2 shows the correlation analysis results.

Correlations					
		S/S_0	Relative Humidity (φ)	ΔT	Wind Speed (c_w)
H/Ho	Pearson Correlation	0.502**	-0.457**	0.486**	-0.091**
	Sig. (2-tailed)	0.000	0.000	0.000	0.002
	N	1188	1188	1188	1188

**. Correlation is significant at the 0.01 level (2-tailed).

Table 2: Correlation analysis result for the weather elements

3. MODEL FORMULATION AND VALIDATION

3.1. Model formulation

Developing a generalized model for solar radiation requires selecting the appropriate weather elements which serves as predictor in the models. A multiple linear regression is run on the dependent variable H/H_o against all the selected predictors and any elements whose coefficient is zero was dropped from the model. The regression equation is of the form;

$$y = a + \sum_{i=1}^{n} b_i x_i \pm e \quad (3)$$

The variable y being the dependent variable H/H_o, 'a' is a constant; b_i is the empirically determined coefficient for the selected weather element x_i and 'e' is the standard error of estimation. The developed generalized model with the standard error of estimate is as follow.

$$\frac{H}{H_0} = 0.441 + 0.183\left(\frac{S}{S_0}\right) - 0.001\varphi - 0.006(c_W) + 0.005(\Delta T)$$

$$e = \pm 8.6019\% \quad (4)$$

S_o is the maximum monthly average daily available sunshine hour and is given by Eq. 5 [3]. The sunset hour angle ω_s is obtained using Eq. 6 and the solar declination δ using Eq. 7. n_d is the average month day as expressed by [3].

$$S_0 = 2\omega_S/15 \quad (5)$$

$$\cos\omega_s = -\frac{\sin\phi\sin\delta}{\cos\phi\cos\delta} = -\tan\phi\tan\delta \quad (6)$$

$$\delta = 23.45\sin\left(360\frac{284+n_d}{365}\right) \quad (7)$$

3.2. Model Validation

The following statistical tools are used to evaluate the developed model against the measured data. $H_{c,i}$, $H_{m,i}$ are the calculated and measured solar radiation respectively while n = 12, the number of months in a year.

$$MBE = \sum_{i=1}^{n}(H_{c,i} - H_{m,i})/n \quad (8)$$

$$MABE = \sum_{i=1}^{n}\left|(H_{c,i} - H_{m,i})\right|/n \quad (9)$$

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|(H_{c,i} - H_{m,i})/H_{m,i}\right|\times 100 \quad (10)$$

$$RMSE = \sqrt{\sum_{i=1}^{n}\left(H_{c,i} - H_{m,i}\right)^2/n} \quad (11)$$

$$R^2 = \left[1 - \left(\frac{\sum_{i=1}^{n}\left|H_{c,i} - H_{m,i}\right|^2}{\sum_{i=1}^{n}H_{m,i}}\right)\right] \quad (12)$$

MBE; the mean bias error gives the overall long term performance of the model, MABE is the mean absolute bias error and it gives the general overview of the error regardless of overestimation or underestimation. MAPE is the mean absolute percentage error and RMSE, the root mean square error is good in evaluating the short term performance of the model while R^2 is the model fitness.

4. RESULTS AND DISCUSSION

Table 3 shows the measured and calculated values of H with their respective statistics while figures 1(a – i) show the corresponding graphs for different locations considered.

The model performs averagely for location 1, with the least coefficient of determination, $R^2 = 0.569$ and well above average for the rest of the locations and with location 7 having the largest coefficient of determination $R^2 = 0.955$.

MABE and MAPE are highest for location 1 and smallest for location 7. The RMSE value is highest for location 1 and smallest for location 9.

The value of MBE is found to be highest for location 8 and smallest for location 1, but MBE is not a reliable means of measuring model performance due to its inherent unfair error cancellation.

MONTH	LOCATION																	
	1		2		3		4		5		6		7		8		9	
	^aH_m	H_c	^aH_m	H_c	^aH_m	H_c	^aH_m	H_c	^aH_m	H_c	^aH_m	H_c	^aH_m	H_c	^aH_m	H_c	^aH_m	H_c
JAN	17.96	21.14	20.26	22.53	21.85	21.96	21.34	22.96	20.06	22.93	27.20	25.00	28.28	26.74	20.58	19.93	23.79	24.79
FEB	18.39	19.96	20.32	21.72	22.41	20.88	23.32	22.35	20.15	22.08	22.51	22.57	23.40	24.24	18.68	18.55	20.49	21.03
MAR	16.06	17.95	17.83	19.36	19.59	18.63	20.07	19.64	17.49	19.65	19.44	18.81	21.95	21.28	17.73	16.2	19.57	18.7
APR	13.06	14.71	15.00	16.76	16.27	15.83	16.88	16.92	14.88	16.65	14.57	13.92	17.19	17.32	14.62	13.14	16.18	15.37
MAY	11.28	12.34	14.58	15.24	15.21	14.07	15.63	14.69	13.83	14.65	8.93	9.81	14.31	14.09	12.03	10.59	13.54	12.94
JUN	10.65	10.80	13.27	13.64	13.71	12.82	14.17	13.41	12.70	13.23	7.97	8.36	12.52	12.73	10.69	9.38	12.24	11.43
JUL	11.74	11.70	13.86	14.61	14.76	13.51	15.26	14.23	13.35	14.12	8.87	9.29	14.08	13.41	12.06	9.94	13.48	12.6
AUG	13.60	14.25	16.55	17.12	16.69	15.96	17.82	16.37	16.19	16.83	10.76	11.59	17.23	16.46	14.32	12.18	16.40	15.74
SEP	15.11	17.01	19.79	20.36	19.39	19.14	22.67	20.36	20.26	20.62	14.12	15.68	21.71	20.69	17.37	14.7	20.09	19.26
OCT	15.51	19.17	20.94	21.98	18.21	20.49	23.73	22.06	20.70	22.52	18.96	20.42	24.74	24.03	18.68	17.63	22.73	22.08
NOV	16.83	21.24	19.84	22.17	19.41	21.3	23.72	22.61	21.70	23.89	24.60	26.18	26.98	26.53	20.50	19.4	25.73	23.94
DEC	17.15	21.58	16.70	22.31	21.17	22.28	24.78	23.48	22.86	24.25	24.54	25.02	30.17	27.94	21.43	20.45	26.27	24.91
MBE	-2.04		-1.57		0.15		0.859		-1.44		-0.35		0.592		1.383		0.643	
MABE	2.049		1.572		1.048		1.136		1.438		0.928		0.788		1.383		0.9	
MAPE	12.9		6.181		5.88		5.629		7.891		5.865		3.493		9.19		4.751	
RMSE	6.185		2.088		1.215		1.272		1.63		1.109		0.975		1.534		0.962	
R^2	0.569		0.75		0.919		0.919		0.851		0.927		0.955		0.858		0.952	

Table 3: Measured and computed global radiation for the nine provinces ([a] Source: ARC, 2012)

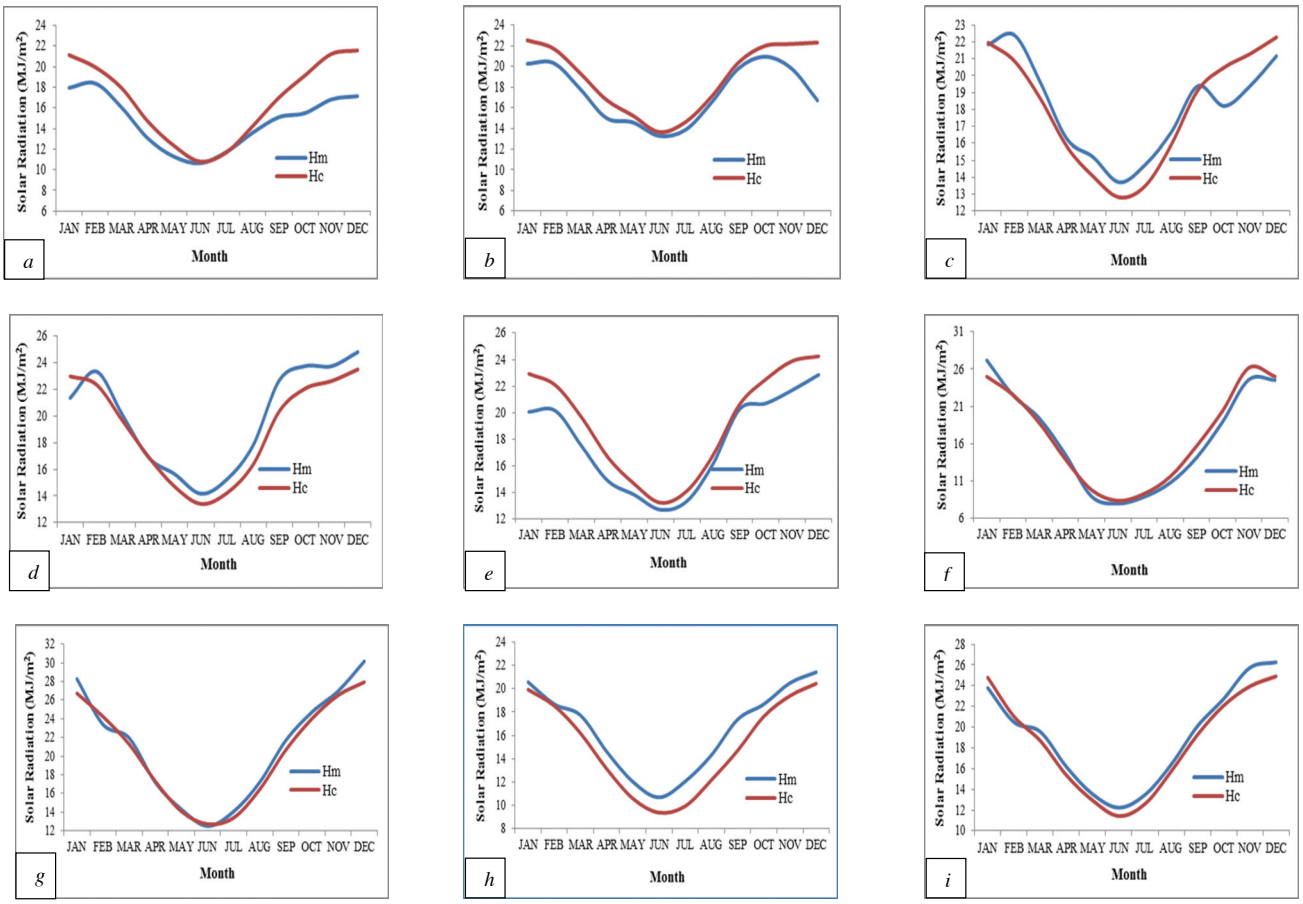

Fig. 1(a – i): Measured, H_m, and Computed, H_c, Monthly Average Daily Solar Radiation

5. CONCLUSION

The developed model performed above average for all the locations, so, it can be used to calculate the GSR for South Africa provinces, but care must be taken when it is being used in Kwazulu-Natal (location 1) as its results is least accurate for this province, hence, there is the need for further research to improve accuracy for this location.

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