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FEW SITE-INDEPENDENT MODELS FOR ESTIMATING GLOBAL SOLAR RADIATION FOR WEST AND SOUTH ASIAN COUNTRIES

Iranna Korachagaon[1], V.N. Bapat[2] and Irfan Anjum Badruddin[3]
[1]Electrical Engineering Department, Annasaheb Dange College of Engineering & Technology
Ashta – 416 301, Dist. Sangli, Maharashtra State, India.
[2]Freelance Consultant, Jee Systems & Services, Sahayog Nagar,
Kupwad, Sangli – 416 416, India.
[3]Department of Mechanical Engineering, University of Malaya
50603 Kuala Lumpur, Malaysia
Email: irfan_magami@Rediffmail.com

ABSTRACT

Knowledge of the global solar radiation (GSR) at a place is necessary in selecting the suitable site for implementing solar energy projects. For under-developed and developing countries, there is a very low spatial density of meteorological stations equipped for radiation observation. Hence, the numerical methods become a useful alternative. Here, measured data of geographical and meteorological (geo-met) parameters of 90 stations across Asian countries is used to develop site-independent GSR estimation models. These parameters are longitude (φ), latitude (λ), mean sea level (MSL) and daily averages of maximum air temperature (T_{max}), minimum temperature (T_{min}), percentage relative humidity (%RH), temperature difference (ΔT) & ratio of minimum to maximum temperature (T_{min}/ T_{max}). Apart from the above data, data from 5 other stations is used for model validation. Root mean square error (RMSE) is used to assess the quality of the GSR estimates. 6 new models considering different combinations of geo-met parameters as variables are proposed. Observed RMSE ranges from 3.3% to 4.4%. With the test data, new model M-3 (with φ & %RH as variables) gives RMSE of 2.9% and the simplest model M-5 (with MSL, φ, λ, & %RH as variables) gives a RMSE of 1.87%.

***Keywords**:* Global solar radiation; Latitude; Longitude; Temperature

1 INTRODUCTION

Global solar radiation (GSR) is the sum of direct solar radiation and diffuse solar radiation at any place on a horizontal plane on earth surface. Generally GSR is measured in watts per unit area. Information about the GSR is required in many applications, ranging from crop growth models, evapo-transpiration estimates to design photovoltaic systems, solar collectors, solar crop drying systems and buildings. Obviously, measured data are the best sources of this information. Unfortunately in developing countries, metrological stations hardly measure GSR.

To derive the detailed solar radiation climatology of a region and to estimate its solar energy potential, it is necessary to collect extensive radiation data of high accuracy at a large number of stations covering all climatic zones of the region. It was suggested by Pivovsrova (1978) that, for regions with strong gradients such as coastal and mountainous areas, station-to-station spacing required would be 100 km to 200 km. On planes, spacing of 500 km would be adequate. High-quality information on solar resources is the key factor for site selection for renewable energy projects. Lot of time & effort may be required to collect the solar radiation data by actual measurements depending on the site conditions. Hence GSR estimation models become necessary in obtaining the GSR estimate at a given location. Using S/S_o & *%RH* data, (Swarthman and Ogunlade, 1967) GSR estimation for the particular location is possible. Other GSR models (Gopinathan, 1988; Raja, 1994) used S/S_o, *%RH*, λ, T_{ave} as variables. Few researchers (Allen, 1997; Bristow & Campbell, 1984; Chandel et al., 2005) proposed models with ΔT. Other studies (Zhou et al., 2006; Prescott, 1940; Page, 1961) employed only sunshine duration for predicting GSR for different places in the world. With S/S_o, (Bahel et al., 1987) proposed a worldwide model. Using cloud coverage data (Black, 1956) from many parts of the world, proposed quadratic equation model to estimate GSR. As said in 1988 IEA report (Daryl, 2005) – “at the beginning of 21st century, present solar radiation models and measurements are rather comparable, with absolute measurement uncertainties in the order of 25-100 W/m^2 in hemispherical measured data. The challenge for solar radiation measurements and models is to reduce the uncertainties in measured data, as well as develop more robust mathematical models i.e fewer input parameters and smaller residuals, under a wider variety of conditions”. Considering the above factors, there exists an immediate need for the site-independent mathematical model to estimate the GSR. Hence this work includes, (1) validating the existing global models with the data from considered region; (2) To propose new site-independent models with easily available geo-met parameters as variables (3) To validate so proposed models with the test data and (4) To estimate GSR with %RH in place of S/So.

2 DATA

In the considered region of Asia, data at 95 meteorological stations is continuously recorded since 1967 (ASHARE 2005 & Mani 1981). The data from these locations, such as *φ, λ, MSL,* T_{max}, T_{min}, *%RH,* S/S_o is available as the basic data. For our convenience ΔT & (T_{min}/T_{max}) data is derived from the basic data as tabulated in Appendix – I.

These 95 locations are spread across the Asian region as shown in Figure 1. Of 95 stations, data from 90 stations is used for developing the models & data from 5 stations is used for validating the models proposed.

3 BASIC RELATIONS

The monthly average daily extraterrestrial solar radiation on a horizontal surface is calculated by

$$H_o = \frac{24}{\pi} I_o f \left[\cos\lambda \cos\delta \sin\varpi_s + \frac{\pi}{180} \varpi_s \sin\lambda \sin\delta \right] \quad (1)$$

where I_o is the solar constant, f is the eccentricity correction factor for varying earth-sun distance, λ is the latitude of the site, δ is the solar declination angle and ω_s is the mean sunrise hour angle for the given month.

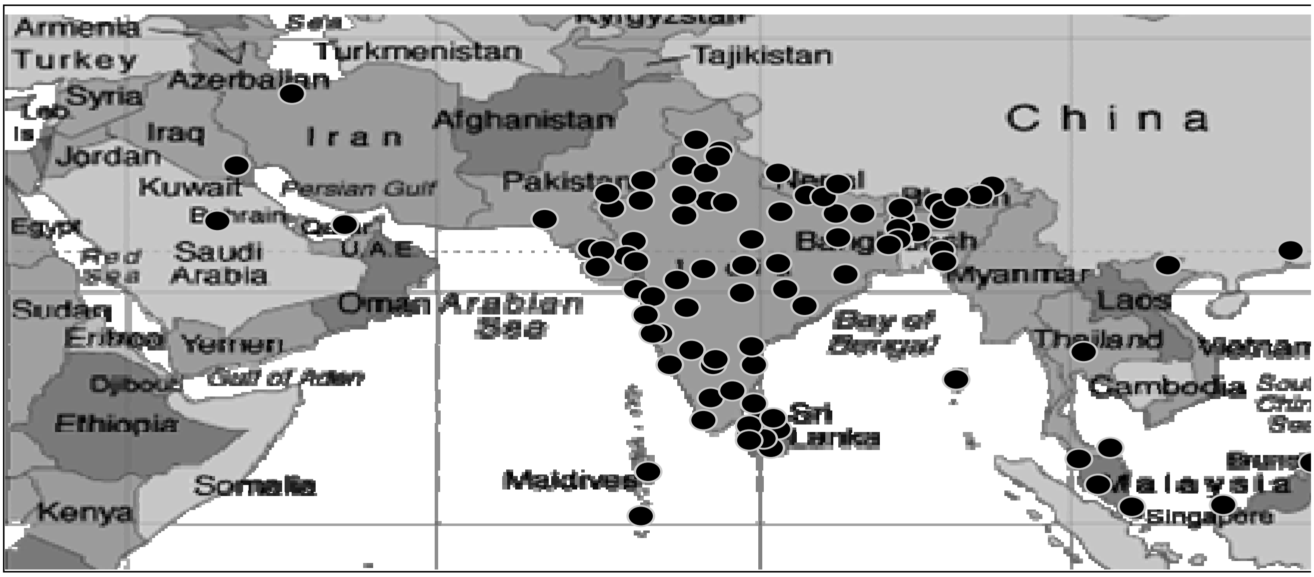

Fig. 1. Network of meteorological stations

The eccentricity correction factor, solar declination angle and sunrise hour angle can be computed by equations (2) – (4), respectively (Rai 2005):

$$f = 1 + 0.33 \left[\cos\left(\frac{360n}{365} \right) \right] \quad (2)$$

$$\delta = 23.45 \sin\left[\frac{360(284 + n)}{365} \right] \quad (3)$$

$$\omega_s = \cos^{-1}(-\tan\lambda \tan\delta) \quad (4)$$

where, n is the number of the day of the year starting from the first of January. For a given month, the maximum possible sunshine duration S_o, can be calculated as

$$S_o = \frac{2}{15} \omega_s \quad (5)$$

GSR measured on the horizontal surface on earth (H_g) is generally referred with respect to the extra terrestrial solar radiation (H_o) and computations are done with the relation (H_g / H_o).

4 ESTIMATION MODELS

The first empirical relation is proposed by Angstrom which is modified by Prescott and is known as Angstrom-Prescott model and is given by,

$$\frac{H_g}{H_o} = a + b\left(\frac{S}{S_o}\right) \qquad (6)$$

a, b are site dependent empirical coefficients.

Page gave the coefficients of the Angstrom-Prescott model, which is believed to be applicable anywhere in the world, as given below;

$$\frac{H_g}{H_o} = 0.23 + 0.48\frac{S}{S_o} \qquad (7)$$

Bahel developed a worldwide relation based on sunshine hours and GSR data of 48 stations around the world, with varied meteorological conditions and wide distribution of geographical locations:

$$\frac{H_g}{H_o} = 0.16 + 0.87\left(\frac{S}{S_o}\right) - 0.16\left(\frac{S}{S_o}\right)^2 + 0.34\left(\frac{S}{S_o}\right)^3 \qquad 8)$$

Gopinathan introduced a multiple linear regression equation of the form:

$$\frac{H_g}{H_0} = a + b\cos\lambda + cZ + d\left(\frac{S}{S_o}\right) + eT_{ave} + fRH \qquad (9)$$

Swarthman and Ogunlade stated that the global radiation can be expressed as

$$H = a\left(\frac{S}{S_o}\right)^b RH^C \qquad (10)$$

$$H = a + b\left(\frac{S}{S_o}\right) + cRH \qquad (11)$$

Allen suggested a self calibrating model that is a function of the mean monthly maximum and minimum temperatures:

$$\frac{H}{H_o} = \left[a\sqrt{(T_{\max} - T_{\min})}\right] = a\sqrt{\Delta T} \qquad (12)$$

Bristow and Campbell suggested the following relationship for daily global solar radiation as a function of daily extraterrestrial radiation and the difference between the maximum and minimum air temperatures

$$\frac{H}{H_o} = a\left[1 - \exp\left(-b\Delta T^C\right)\right] \qquad (13)$$

5 METHODS OF MODELS EVALUATION

Root mean square error (RMSE)

The performance of the models is generally evaluated in terms statistical error tests such as root mean square error (RMSE) which is given as,

$$RMSE = \sqrt{\frac{\sum_{i=1}^{k}(H_{ic} - H_{im})^2}{k}} \qquad (14)$$

Where H_{im} is the i^{th} measured value, H_{ic} is the i^{th} estimated value and k is the total number of observations.

Existing estimation models referred in equations 12 & 13, when evaluated with data from Appendix-I using Datafit 8.2 software tool (www.curvefit.com), give the RMSE values as shown in Table 1. Other models in equations 7-11, are not evaluated as these models require sunshine duration data, which is not available for all the stations under consideration. The tick marks indicates the variables used in the model.

Table 1. RMSEs computed for existing models for the data from Asian Countries

SN	Model	ΔT	RMSE
1	Bristow & Campbell (B&C) Model	✓	6.03%
2	Allen Model	✓	10.92%

Correlation coefficient

Correlation coefficient indicates the strength and direction of a linear relationship between two random variables. The Pearson correlation coefficient of series *X* and *Y* is

$$r = \frac{\sum(x - x_a)(y - y_a)}{\sqrt{\sum(x - x_a)^2 \sum(y - y_a)^2}} \qquad (15)$$

Where, x and y are the series elements while x_a and y_a are the series averages. The correlation coefficient is interpreted as low, medium or high depending on the value of *'r'*, as given in the Table 2.

Table 2. Interpretation of Correlation Coefficient

Correlation	Low	Medium	High
Positive	0.10 to 0.29	0.30 to 0.49	0.50 to 1.00
Negative	−0.29 to −0.10	−0.49 to −0.30	−1.00 to −0.50

Table 3 presents correlation coefficients for correlations of different parameters with GSR, computed from the geo-met data of 90 stations from Appendix I.

DATA ANALYSIS

GSR is estimated using 6 new site independent models obtained here. The RMS error has been computed for each of these models. The same is presented in Table 4. Equations for models M-1 to M-6 are given in Appendix – II.

Table 3. Correlation coefficients of different parameters with GSR for the data in Appendix – I

Parameter	*MSL*	T_{min}	T_{min}/T_{max}	ΔT	T_{max}	φ	λ	%RH
Correlation Coefficient	0.119	-0.079	-0.0948	0.145	0.1126	-0.783	0.23	-0.646

Table 4. RMSE values for new site-independent models proposed, for the data in Appendix – I

Model	*MSL*	T_{min}	T_{min}/T_{max}	ΔT	T_{max}	φ	λ	%RH	RMSE
M-1								✓	4.4%
M-2						✓			3.4%
M-3						✓		✓	3.3%
M-4						✓	✓	✓	3.6%
M-5	✓					✓	✓	✓	3.6%
M-6	✓	✓	✓	✓	✓	✓	✓	✓	3.5%

6 RESULTS AND ANALYSIS

Observations

- It is seen from Table 1 that, the RMSE values for existing B&C model and Allen model are 6.03% & 10.92% for the data from Asian countries considered.
- It is observed from Table 3 that,
  - φ and %RH have high, but negative correlation with GSR.
  - All other parameters have low correlations with GSR.
- From Table 4, It can be seen that
  - The models obtained by curve fitting technique have wide variation in number of variables. They range from 1-variable models to 8-variables models.
  - Interestingly, RMSE varies over a narrow range from 3.3% to 4.4% for these 6 models.
  - Models with *%RH and φ* give the RMSEs in still narrower range from 3.3% to 3.6%, implying major influence of these parameters in GSR estimation accuracy.

Model M-3 with RMSE 3.3%, given below is the best from the point of view of the value of RMS error.

M-3 $$\frac{H_g}{H_o} = a + b\cdot\phi + c\cdot RH + d\cdot\phi^2 + e\cdot RH^2 + f\cdot\phi\cdot RH + g\cdot\phi^3 + h\cdot RH^3 + i\cdot\phi\cdot RH^2 + j\cdot\phi^2\cdot RH \quad (16)$$

Table 5. Data from other stations (Test Data)

S N	Station	MSL	φ	λ	T_{min}	T_{max}	T_{min}/T_{max}	ΔT	%RH	Hg/Ho
1	AS-IND-Bhubneshwar	46	85.82	20.25	19.27	37.04	0.52	17.78	76.17	0.53
2	AS-IND-Kota	274	75.80	25.13	18.06	36.37	0.50	18.31	51.42	0.56
3	AS-IND-Surat	12	72.82	21.35	20.38	35.53	0.57	15.15	67.42	0.53
4	AS-LKA-Ratmalana	5	79.86	6.81	21.73	32.30	0.67	10.58	80.92	0.54
5	AS-MYS-Kuching	27	109.32	1.46	22.05	33.08	0.67	11.03	86.00	0.42

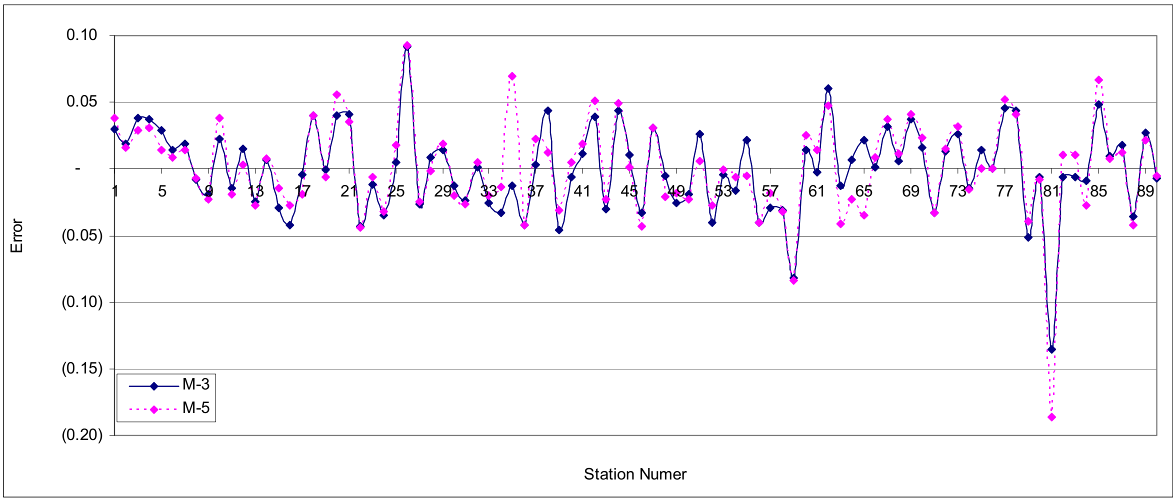

Fig. 2. Errors of the estimated GSR w.r.t. measured values

Table 6. Comparison between the measured and estimated values of Hg/Ho (GSR) for test data

SN	Station	Measured	M-3 Estimate	M-5 Estimate
1	AS-IND-Bhubneshwar	0.532	0.5179	0.5194
2	AS-IND-Kota	0.565	0.5735	0.5705
3	AS-IND-Surat	0.533	0.5775	0.5641
4	AS-LKA-Ratmalana	0.536	0.5345	0.5316
5	AS-MYS-Kuching	0.421	0.4652	0.445
	RMSE		2.90%	1.87%

Further the model M-5, also appears to be competent because of its structural simplicity with reasonably low RMSE of 3.6%

$$\frac{H_g}{H_o} = a \cdot MSL + b \cdot \phi + c \cdot \lambda + d \cdot RH + e \qquad (17)$$

- *%RH* is used in many models, to demonstrate its strength amongst other parameters as is evident from Table 3.
- Depending upon the availability of the data at a location, suitable model can be chosen to estimate GSR.
- Figure 2, indicates the error between the estimated values and the measured values for models M-3 & M-5.
- Test data is given in Table 5. For this data all the proposed models listed in Appendix- II, are validated. It is noted that, for these stations, S/S_o data is not available.
- Models M-3 & M-5 are validated with data in Table 5 and results are given in Table 6. The values of RMSE are 2.90% and 1.87% respectively. These fairly low values indicate robustness of these models.

7 CONCLUSION

In this work, a number of alternatives to the traditional Angstrom's model are proposed. These new site independent models are comprised of polynomials and linear derived relationships. Relative humidity, amongst the 8 parameters chosen for the study, exhibit strongest correlationship with GSR. Incidentally, %RH data is readily available in all meteorological stations. The models are evolved from the data at 90 stations across the length and breadth of Asian countries. Therefore, a fair degree of site independence is achieved in the model. Further the data from remaining 5 stations was used to validate the models. The models exhibited good performance which reflected in low RMS Error.

NOMENCLATURE

GSR	Global Solar Radiation
φ	Longitude

λ	Latitude
MSL	Mean Sea Level
T_{max}	Maximum Air Temperature
T_{min}	Minimum Air Temperature
T_{ave}	Average Air Temperature
%RH	Percentage Relative Humidity
S/S_o	Ratio of Sunshine Duration
ΔT	$(T_{max} - T_{min})$
Hg	Measured or Estimated GSR
Ho	Extra-terrestrial GSR
AS	Asia
ARE	United Arab Emerites
BGD	Bangladesh
IND	India
KWT	Kuwait
LKA	Sri Lanka
MAC	Macau
MDV	Maldives
NPL	Nepal
PAK	Pakistan
SAU	Saudi Arabia
THA	Thailand
TWN	Taiwan
VNM	Vietnam
BRN	Brunei
MYS	Malaysia
PHL	Philippines
SGP	Singapore

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