

Model Development for Predicting Solar Radiation under Clear and Overcast Skies

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Abstract
Models to enable estimation of monthly mean global solar radiation from air temperature, relative humidity and rainfall measurements were developed. The multivariable models were developed for days on which the probabilities of clear and overcast skies are maximum using a range of five years meteorological data (2002–2006) obtained from Nigerian Meteorological Agency (NIMET) for the city of Kaduna in Nigeria. Also, a one year data of (2010) for the city was used to test the performance of the models with some results giving equality, underestimation or overestimation compared to the measured values. The months of clear skies were identified to be October through March and that of overcast skies to be April through September. The highest and lowest atmospheric transmittance, *k*, values were 0.42 and 0.12. 2002 clear sky model gave 21.66 $MJm^{-2}day^{-1}$ as January 2010 predicted solar radiation which is an underestimation when compared to the measured value of 26.30 $MJm^{-2}day^{-1}$ while the overcast sky model gave 24.01 $MJm^{-2}day^{-1}$ for April 2010 which compared to the measured value of 22.30 $MJm^{-2}day^{-1}$ is an overestimation. In other instances, equality between the predicted and measured values were observed. The highest and lowest values of the coefficient of determination, R^2, obtained are 0.99 and 0.56. However, rain data were used in the development of overcast skies models only. The highest and lowest values of the MPE were 0.02 and -1.76. Other statistical indicator tests (RMSE and MBE) were carried out to further validate the models showed that the estimated values of the global solar radiation were in good agreement with the measured values. These models are therefore recommended for utilization by designers and engineers of solar energy systems in Kaduna and other localities having similar weather patterns.
Keywords: model, predicting, solar, radiation, clear, overcast, skies.

1. Introduction

Given the fundamental role that energy plays to all human activities and in view of the scarce and depleting fossil fuel reserves, the perennial energy crisis in the world has necessitated the finding of alternative sources of energy. Inadequate supply of energy restricts socio-economic activities, hinders meaningful development in any sector as well as adversely affects the quality of life in any nation. Amongst the various types of clean and renewable sources, solar energy appears to be the most favoured option because of its infinite and non-polluting nature. The knowledge of the availability of global solar radiation and its components for a given area is essential in order to utilize the available solar energy economically and efficiently. According to Bolaji [1], solar energy is an ideal alternative source of energy because it is abundant and inexhaustible. Solar energy availability is quite abundant in Nigeria because of its tropical location; hence Nigeria is viable for solar energy technology applications [2].

The amount of solar radiation at any site is best determined through the installation of measuring instruments such as the pyranometer at that particular place for monitoring and storing its day-to-day recording. But this is a very tedious and costly exercise, hence the need for an alternative method of determination in form of mathematical models.

The meteorology of a geographical location influences the availability of solar radiation at that location. Since solar radiation measurement is not having total coverage for all locations in most developing nations, it has become a commonplace to estimate the solar radiation reaching a surface from meteorological indicators like sunshine hours, temperature, relative humidity and rainfall, to name but a few [3]. Several correlations and models have been developed by various investigators for estimating monthly mean global solar radiation. These methods base their estimations on meteorological data of the location.

Good prediction of the global solar radiation for a given location requires, in principle, a long term average meteorological data which are still scarce for many locations around the world. Therefore, it is not always possible to predict the value of clear sky solar radiation with reasonable accuracy, and hence a continuous study is going on for the improvement of theoretical models [4]. In order to improve the accuracy of a model, some investigators also incorporated various parameters such as zenith angle and latitude. However, these models suffer with varying degrees of complications, maybe because of the lower number of measuring data, and hence cannot give accuracy in predicting the results.

The present work intends to develop models to estimate solar radiation under clear and overcast sky conditions on the basis of maximum temperature, relative humidity and rainfall measurements. The model first identifies if a particular month has a high probability of being either clear or overcast. This is done on the basis of sky transmittance, *k*, which is a function of the Linke's turbidity, T_L, and site elevation, *h*. This probability is assumed to increase if rainfall is absent (clear sky) and to decrease if rainfall is present (overcast sky).

2. Materials and Methods

2.1 Materials

Meteorological data comprising of the daily records of solar radiation, maximum temperature, relative humidity and rainfall measured in Kaduna for five years (2002-2006) were obtained from the Nigerian Meteorological Agency (NIMET) for developing the models. The same set of data for a period of one year (i.e. 2010) for the same location were also obtained and used to test the performance of the developed models. The daily values were then converted to monthly average values. The solar radiation in unit of $MJm^{-2}day^{-1}$ represents the measured global solar radiation, H_m, for the experimental period.

2.2 Methods

2.2.1 Determination of Solar Radiation Parameters

The monthly mean daily extraterrestrial solar radiation, H_0, values were calculated using the expression [5]:

$$H_0 = \frac{24}{\pi} I_{sc} E_0 \left(\frac{\pi}{180}\omega \sin\phi \sin\delta + \cos\phi\cos\delta\sin\omega\right) \quad \ldots (1)$$

where I_{sc} is the solar constant in $MJm^{-2}day$

$$I_{sc} = \frac{1366 \: x \: 3600}{10^6} \quad (MJm^{-2}day^{-1}) \quad \ldots. (2)$$

E_0 is the eccentricity correction factor given by;

$$E_0 = 1 + 0.033\cos\left(\frac{360 \: x \: n}{366}\right) \quad \ldots. (3)$$

ω is the solar hour angle given by;

$$\omega = cos^{-1}[-\tan(\phi)\tan(\delta)] \quad \ldots (4)$$

ϕ is the latitude of the location.

δ is the sun's declination angle given by;

$$\delta = 23.5^0 sin\left[\frac{360(284+n)}{366}\right] \quad \ldots (5)$$

where n is the characteristic day number for each month: n = 1 on 1st January to 365 on 31st December.

The Linke's turbidity factor is expressed as [6];

$$T_L = \frac{1}{m_A \delta_R} \ln\left(\frac{H_0}{H_n}\right) \quad \ldots (6)$$

where H_n is the direct normal irradiance expressed as;

$$H_n = 950.2\left(1 - e^{(-0.075(90^\circ - \theta_z))}\right) \quad \ldots (7)$$

θ_z is the zenith angle expressed by;

$$\theta_z = cos^{-1}[\sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\cos(\omega)] \quad \ldots (8)$$

δ_R is the spectrally integrated optical thickness of the clean dry atmosphere given by Louche [7];

$$\delta_R = \frac{1}{10.4 + 0.718 m_A} \quad \ldots (9)$$

m_A is the relative optical air mass expressed as;

$$m_A = \left(\frac{p}{101.3}\right)\frac{1}{cos\theta_z + 0.15(93.885 - \theta_z)^{-1.253}} \quad \ldots (10)$$

The atmospheric pressure p can be estimated from the relationship;

$$p = 101.3e^{-\left(a/8200\right)} \quad \ldots (11)$$

where a is the elevation of the site.

When the value of T_L is estimated for a given location, for a given day of the year and for a given solar elevation, the sky transmittance of a clear sky is calculated according to the modified Beer's law equation as [8]:

$$k = 0.83e^{(-0.026T_L/\sin h)} \quad \ldots (12)$$

Where h is the solar elevation given by:

$$h = sin^{-1}[\omega\sin\phi + \cos\delta\cos\phi\cos\omega] \quad \ldots (13)$$

The clearness index is an indication of the bulk transmittance of the atmosphere, even one containing clouds. The clearness index for a particular solar component is computed as the ratio of the measured value to the equivalent maximal component based on the extraterrestrial radiation above the atmosphere. Thus, for horizontal surfaces, the clearness index K_T is expressed as [9]:

$$K_T = \frac{H_m}{H_0} \quad \ldots (14)$$

2.2.2 Identification of Clear and Overcast Skies

The solar radiation that reaches the earth surface is a function of the solar constant, sine of the solar elevation, the relative air mass and the turbidity factor of the air mass. Turbidity in turn depends on the transmittance due to molecular (Rayleigh) scattering, ozone absorption, uniformly mixed gases, water vapour and aerosols [10]. The aforementioned factors were taken into account in determining the atmospheric transmittance, k, as indicated by equation (12), hence, it was taken that the higher the atmospheric transmittance, the clearer the sky and vice versa. Therefore, months in which the probabilities of clear or overcast skies are maximum were recognized by taking a range of values of the atmospheric transmittance as indicated in table 2.

2.2.3 Model Development

The models were developed by carrying out multiple regression between the clearness index, K_T, as the dependent variable and maximum temperature, *T,* relative humidity, *RH*, and rainfall, *R*, as the independent variables in order to determine the coefficients of each independent variable. These coefficients along with the extrateresstrial solar radiation calculated were used to develop the models for both clear and overcast skies. Rainfall was neglected in the clear skies' models because it is taken that the atmospheric transmittance increases if rainfall is absent and decreases if rainfall is present as a result of high precipitable water content and cloud cover in the atmosphere during rainy season which greatly attenuates transmittance of solar radiation. Some of the parameters determined are tabulated in table 1.

2.2.4 Model Test

The models were tested by using them to predict the monthly mean global solar radiation for the year 2010.

2.2.5 Model Validation

The accuracy and applicability of the models were determined based on analysis of different statistical indicators. These are the mean bias error (MBE), root mean square error (RMSE) and the mean percentage error (MPE) methods. A positive MBE value gives the average amount of overestimation in the predicted values and vice versa. A low MBE is desirable [11]. The RMSE is always positive but a zero value is desirable [12]. A low value of MPE is desirable. The expressions for evaluating the values of the MBE, RMSE and MPE are given below:

$$MBE = \frac{1}{N}\sum_{n=1}^{n}\left(H_p - H_m\right) \quad \dots (15)$$

$$RMSE = \sqrt{\left[\frac{1}{N}\sum_{n=1}^{n}\left(H_p - H_m\right)^2\right]} \quad \dots (16)$$

$$MPE = \frac{1}{N}\sum_{n=1}^{n}\left[\frac{H_m - H_p}{H_m} \times 100\right] \quad \dots (17)$$

where H_p and H_m are the predicted and measured values of solar radiation and *N* is the total number of observations.

Results of the statistical tests carried out are presented in table 7.

3. Results and Discussion

3.1 Results

Table 1: Summary of results of solar radiation analyses for Kaduna.

S/N	Months	Extraterrestrial Solar Rad. H_0 (MJm^{-2}day)	Normal Irradiance H_n (MJm^{-2}day)	Air Mass m_A	Linke's Turbidity T_L	Atmospheric Transmittance k
1	Jan.	31.45	0.101	29.73	6.44	0.42
2	Feb.	33.84	0.005	33.67	8.73	0.31
3	Mar.	36.73	0.026	32.81	7.37	0.31
4	Apr.	37.80	0.003	33.76	9.32	0.17
5	May	37.74	0.003	33.76	9.32	0.12
6	Jun.	37.14	0.026	32.81	6.91	0.16
7	Jul.	37.25	0.026	32.81	6.91	0.17
8	Aug.	36.34	0.003	33.76	9.28	0.18
9	Sep.	37.05	0.003	33.76	9.30	0.17
10	Oct.	35.04	0.026	32.81	7.32	0.34
11	Nov.	32.19	0.026	32.81	7.23	0.38
12	Dec.	30.64	0.003	33.76	9.11	0.34

Table 2. Identification of clear and overcast skies for Kaduna

S/N	CLEAR SKIES		OVERCAST SKIES	
	Months	Atmospheric transmittance k	Months	Atmospheric transmittance k
1	January	0.42	April	0.17
2	February	0.31	May	0.12
3	March	0.31	June	0.16
4	October	0.34	July	0.17
5	November	0.38	August	0.18
6	December	0.34	September	0.17

Models developed for both clear and overcast skies by carrying out multiple regressions between the dependent and independent variables for both skies are presented in tables (3) and (4) respectively.

Table 3. Clear Sky Models

S/N	YEAR	MODELS	R^2
1	2002	$\frac{H_p}{H_o} = 0.778205 - 0.00055T - 0.00312RH$	0.87
2	2003	$\frac{H_p}{H_o} = 0.87465 - 0.00354T - 0.00299RH$	0.79
3	2004	$\frac{H_p}{H_o} = 1.049321 - 0.00895T - 0.00286RH$	0.72
4	2005	$\frac{H_p}{H_o} = 0.574553 + 0.004903T - 0.00351RH$	0.56
5	2006	$\frac{H_p}{H_o} = 0.859255 - 0.00314T - 0.00253RH$	0.89

Note: rain parameter was neglected in the clear models

Table 4. Overcast Sky Models

S/N	YEAR	MODELS	R^2
1	2002	$\frac{H_p}{H_o} = 0.788989 - 0.10065T - 0.02961RH - 0.01251R$	0.97
2	2003	$\frac{H_p}{H_o} = -0.66384 + 0.03250T + 0.00272RH + 0.003451R$	0.96
3	2004	$\frac{H_p}{H_o} = 0.197591 + 0.012274T - 0.00023RH - 0.00266R$	0.94
4	2005	$\frac{H_p}{H_o} = 0.019895 + 0.015211T + 0.001205RH - 0.00504R$	0.91
5	2006	$\frac{H_p}{H_o} = -0.72645 + 0.033463T + 0.002684RH + 0.00867R$	0.94

Meteorological data of maximum temperature, relative humidity and rainfall measurements measured in Kaduna in 2010 were used in the clear and overcast skies models developed to predict the global solar radiation and the results compared with measured values. The results are presented in tables (5) and (6) below:

Table 5. Clear sky prediction

S/N	MONTHS	H_m (MJ/m^{2}/day)	H_p (MJ/m^{2}/day)				
			2002 Model	2003 Model	2004 Model	2005 Model	2006 Model
1	Jan.	26.30	21.66	21.67	21.61	20.66	21.93
2	Feb.	26.40	23.39	23.11	22.53	22.86	23.41
3	Mar.	23.70	23.88	24.08	23.45	23.70	24.56
4	Oct.	20.90	20.35	20.75	21.27	18.34	21.58
5	Nov.	24.10	22.06	22.08	22.06	20.99	22.37
6	Dec.	25.40	20.85	20.99	21.26	19.62	21.27

Table 6. Overcast sky prediction

S/N	MONTHS	H_m (MJ/m^{2}/day)	H_p (MJ/m^{2}/day)				
			2002 Model	2003 Model	2004 Model	2005 Model	2006 Model
1	Apr.	22.30	24.01	24.21	24.05	23.48	23.30
2	May	18.80	21.00	22.04	22.21	22.13	21.20
3	Jun.	17.00	15.07	20.24	20.06	19.94	20.19
4	Jul.	15.40	17.74	18.22	19.20	19.18	17.96
5	Aug.	16.50	11.90	18.66	18.27	18.03	19.25
6	Sep.	19.10	12.63	19.42	18.93	18.65	19.99

Table 7. Statistical Test for Kaduna

Model Type	2002			2003			2004			2005			2006		
	MBE	RMSE	MPE	MBE	RMSE	MPE	MBE	RMSE	MPE	MBE	RMSE	MPE	MBE	RMSE	MPE
Clear	-2.44	5.96	1.66	-2.35	5.76	1.60	-2.44	5.97	1.66	-3.44	8.42	2.34	-1.95	4.77	1.33
Overcast	1.89	4.63	-1.73	2.05	5.01	0.02	2.27	5.56	-2.08	1.19	2.91	-1.09	1.92	4.69	-1.76

3.2 Discussion

3.2.1 Clear Sky Prediction

From table (5), the higher values of the measured global solar radiation were recorded in January, February, November and December with March and October giving lower records. For the predicted values however, it is seen that there was steady increase from January to March followed by a decrease in October and then a slight increase in November and December. This can attributed to the fact that these months are not characterized by the presence of rainfall. This is illustrated in figures 1, 3 and 5 in which the curves rises in the months of January, February and March but declines in October before rising again in November and December.

The clear sky models underestimated the global solar radiation in the months of January, February, November and December. But in March and October, the predicted values equaled the measured values. The same pattern is observed in figure 7 but only the month of October in which the estimated global solar radiation is equal to the measured value. In figure 9, the clear sky models overestimated the global solar radiation in March and October and underestimated in the other months.

3.2.2 Overcast Sky Prediction

From table (6), for the measured global solar radiation, the highest records were obtained in April and the lowest records in July, whereas for the predicted values of the solar radiation, the highest records were obtained in April and the lowest records in August. The decrease in radiation could be attributed to the fact that these months constitute the rainy season, and hence the presence of clouds and rain droplets in the atmosphere prevented the surface from receiving more radiation. This is seen in figures 2, 4, 8 and 10 where the lines for the measured global solar radiation falls steadily from April to July and then rises steadily from August to September whereas the predicted values lines falls from April to June then rises slightly in July, falls again in the month of August and finally rises slightly in September.

Figures 2, 6 and 10 indicated that the overcast sky models overestimated the global solar radiation in all the months with the exception of September in which underestimation were obtained. In figure 4, it is seen that the model overestimated the global solar radiation in May, June, July and August but showed that the estimated values are equal to the measured values in the months of April and September. In figure 8 however, the model indicated overestimation in April, May, June and July but showed that the estimated values equals the measured values in August and underestimation in September.

3.2.3 Model Validation

The values of the global solar radiation predicted by the clear sky models were mostly underestimated as indicated by the negative values of the MBE and low MPE, while the values predicted by the overcast sky models were mostly overestimated as a result of the positive values of the MBE and negative values of the MPE. The RMSE on the other hand indicates the level of scatter that a model produces, thus providing a term-by-term comparison of the actual deviation between the predicted and observed values. The lower RMSE values obtained reflects a better model in terms of its absolute deviation.

Summary of the models evaluation is given in Table 7. The results showed that in all the model evaluation methods, the developed models displayed low MBE, MPE and RMSE. This makes the proposed models most suitable for estimating global solar radiation.

In most cases, the proposed models predicted the pattern of the measured solar radiation very well as shown in the figures below:

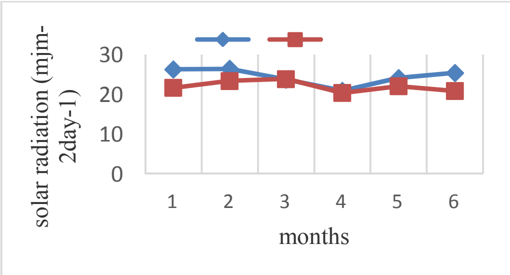

Figure 1. predicted and measured global solar radiation (2002 clear sky model used for the prediction).

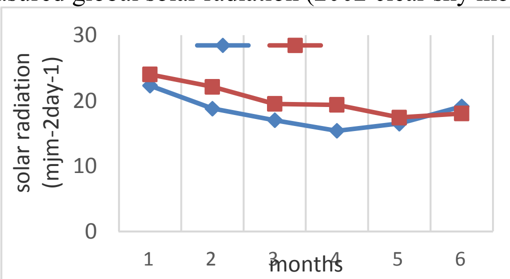

Figure 2. predicted and measured global solar radiation of 2010 (2002 overcast sky model used for the prediction)

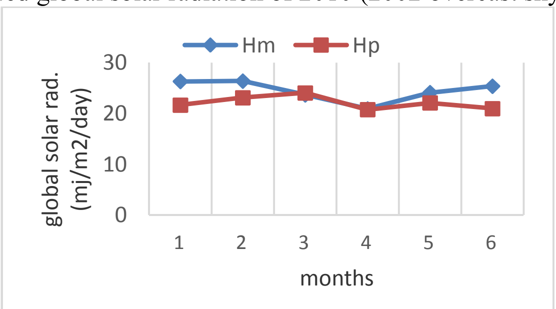

Figure 3. predicted and measured global solar radiation for 2010 (2003 clear sky model used for the prediction).

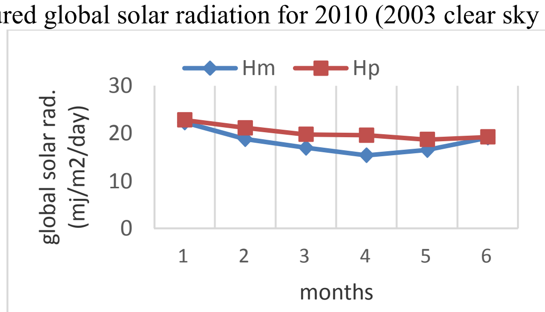

Figure 4. predicted and measured global solar radiation for 2010 (2003 overcast sky model used for the prediction).

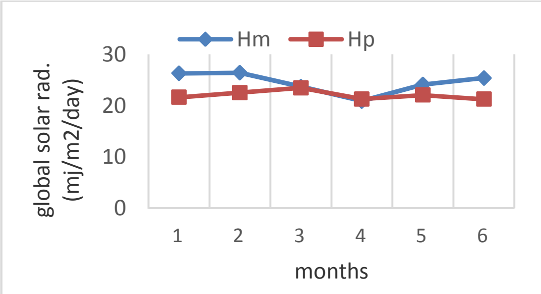

Figure 5. predicted and measured global solar radiation of 2010 (2004 clear sky model used for the prediction).

Figure 6. predicted and measured global solar radiation of 2010 (2004 overcast sky model used for the prediction).

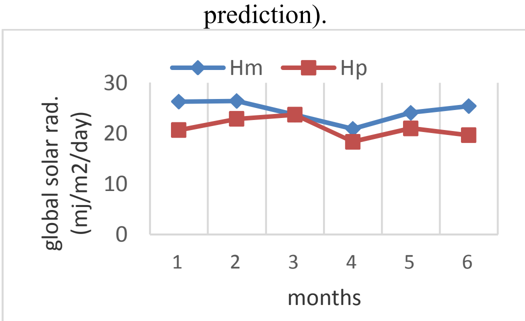

Figure 7. predicted and measured global solar radiation of 2010 (2005 clear sky model used for the prediction).

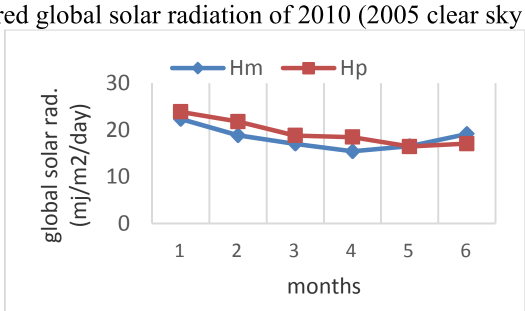

Figure 8. predicted and measured global solar radiation of 2010 (2005 overcast sky model used for the prediction).

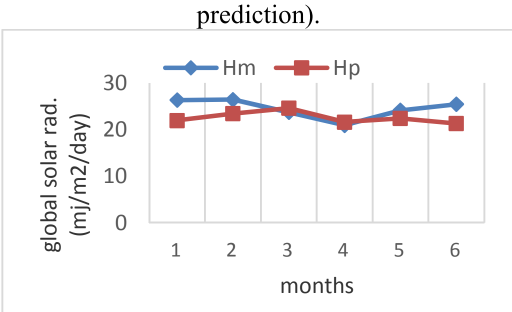

Figure 9. predicted and measured global solar radiation of 2010 (2006 clear sky model used for the prediction).

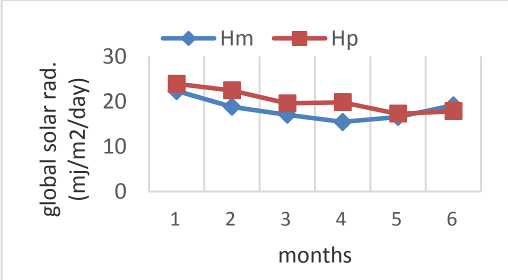

Figure 10. predicted and measured global solar radiation of 2010 (2006 overcast sky model used for the prediction).

4. Conclusion

The results showed that the models developed were able to predict the variability of the monthly mean daily global solar radiation with a very high coefficient of determination, R^2, which indicate that about 70%-90% of variation in the monthly mean daily solar radiation H_m on a horizontal surface can be accounted for.

From tables 4 and 5, as well as the graphical figures, it was observed that the values of the global solar radiation predicted by the models are closely related to the measured values. All clear sky predictions indicated underestimation whereas all the overcast sky predictions indicated overestimation as shown with a few exceptions.

Therefore, the models are adequately fit for predicting global solar radiation under clear and overcast skies in Kaduna and its environs.

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