ANALYSIS OF RATIO OF GLOBAL TO EXTRA-TERRESTRIAL RADIATION (CLEARNESS INDEX) AT SOME TROPICAL LOCATIONS IN INDIA

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Abstract

An attempt has been made to analyze and evaluate the daily average clearness index (H_g/H_0) in terms of daily average cloudiness index (H_d/H_0) for three tropical locations in South India (Chennai, Trivandrum and Visakapatnam). Long term data (15 years, 1993-2007) of measured daily average global and diffuse solar radiation for the locations have been used for this study. Two correlation equations (linear and polynomial) for each location have been developed for clearness index in terms of cloudiness index and found its validity. Performance statistics of the model has been done and applicability of the model is done by comparing the performance statistics with the existing models. It has been found that the proposed model has least error compared with the existing models.

Keywords: *Clearness index, cloudiness index, extra-terrestrial radiation, correlation*

1. Introduction

Measurement of solar radiation is indispensable to utilize solar energy with different designs of thermal devices for various applications. The intensity of direct and global solar radiation on horizontal surface are measured only in selected locations by using extensive solar radiation measuring devices due to cost, maintenance and calibration requirements. Researchers have made sincere efforts to derive empirical models by using measured radiation and recommended the equation for locations where measured data are not available.

Hollands [1] have proposed a theoretical derivation for average diffuse fraction depending on the clearness index and concluded that by adjusting albedo and beam transmittance, the derivation fits the measured data closely. Firoz Ahmed *et al*. [2] have developed two correlations for the estimation of monthly average daily diffuse solar radiation as a function of sunshine hours and clearness index for Karachi. It has been concluded that the diffuse to global ratio is found to be 0.32 and diffuse to extraterrestrial radiation ratio is 0.19 throughout the year. The monthly reference distribution of the daily values of clearness index from measured data of global solar radiation on a horizontal surface has been prepared for eight locations in Iraq by Al-Riahi *et al*. [3] and inferred that the distribution function of daily values of clearness index depends only on their mean value rather the order number of the month during the year. Babatunde and Aro [4] have found the relationship between clearness and cloudiness index at Illorin, Nigeria and concluded that the two ratios are linearly related. A new correlation has been developed between clearness index and relative sunshine for the evaluation of monthly mean daily global radiation by Coppolino [5] at Italian locations. The proposed correlation is found to be suitable for the evaluation of monthly mean daily global solar radiation at Italian locations with a high degree of accuracy. Linear, polynomial, exponential and power regression equations for clearness index in terms of fraction of bright sunshine duration has been derived by using data of 16 meteorological stations in Sudan by Elagib *et al*. [6]. It has been found that the estimated values using regression equations were found to be fall beyond about ±10% accuracy level. Further Sarath Babu and Sathyamurthy [7] have developed correlations for the prediction of minimum and maximum daily clearness indices in the absence of data and tested over 70 locations ranging from 8°N to 64°N. The results have shown that the predicted daily clearness indices have a standard deviation of 0.034 compared with the measured data. Ibanez *et al*. [8] have tested the unimodality of probability density functions of clearness indices at locations between latitudes 18.43°N and 64.81°N. It has been concluded that the proposed bi-exponential method for predicting daily distribution reduced the RMS error by over 20% compared with earlier methods. Harmonic analysis has been used to model the monthly clearness index values at nine stations of Turkey by Ahmet Duran Sahin *et al*. [9] and inferred that the Western and Eastern parts of Turkey have nearly similar characteristics.

Ali Al-Lawati *et al*. [10] have developed radial basis function neural networks for the estimation of clearness index and solar radiation for any location in Oman. The developed maps can be served as reference design and performance evaluation of solar energy conversion systems in the region. Achim Woyte *et al*. [11] have done a localized spectral analysis based on wavelet basis rather than periodic-ones for the prediction of instantaneous clearness index. It has been confirmed that the annual mean values agree well for the different datasets indicating the significant mean square values of the fluctuations as a function of their persistence. An attempt has been made by Ardehali *et al*. [12] to develop a simulation model for analyzing the performance of a water –LiBr solar assisted absorption system with an auxillary heating source and to examine the effects of clearness index data is indispensable for accurate prediction of solar energy collection. The cumulative distribution curves of daily clearness index for 28 locations in Southern Hemisphere has been calculated by Chigueru Tibo *et al*. [13] to enlarge the statistical properties of solar radiation. The results have ratified the conclusions obtained by other authors on the non-universal character of Liu and Jordan cumulative distribution function. Ahwide *et al*. [14] have established a relationship between daily diffuse fraction and daily clearness index by using daily global solar radiation data obtained from three Libyan locations and calculated values of daily clearness index were used to find the frequency of occurrence of days with different values of clearness index and cumulative frequency of occurrence of those days. Further Jamal Hassan [15] has developed empirical equation for monthly mean daily global and diffuse solar radiation by using three year measurements of meteorological data in Mosul and also ARIMA (2,1,1) has been developed for prediction of clearness index. Results have been compared with other available models and it has been confirmed that the calculated values are in close agreement with the measured experimental data with least error.

In the present study, linear and polynomial equations have been developed for daily average clearness index (H_g/H_0) in terms of daily average cloudiness index (H_d/H_g) and validated by finding the standard deviation between calculated and measured data.

2. Methodology

Three South Indian locations viz., Chennai, Trivandrum and Visakapatnam has been selected and long-term measured data of daily average global and diffuse solar radiation during the period from 1993 and 2007 are collected from Indian Meteorological Department, Pune. The latitude and longitude of the locations are presented in tab. 1.

Table. 1 Latitude and Longitude of the locations

Location	Latitude	Longitude
Chennai	13°N	80°E
Trivandrum	8°28'N	76°57'E
Visakapatnam	17°N	83°E

The fifteen year data of daily average global and diffuse radiation for the three locations has been averaged to find the daily average global and diffuse radiation for all the days of the year separately. The daily extra-terrestrial radiation on the locations has been calculated by using the expression

$$H_0 = \frac{24 \times 3600}{\pi} I_{sc} \left[1 + 0.033 \, \text{Cos}\left(\frac{360\, n}{365}\right)\right] \times \left(\text{Cos}\,\phi\, \text{Cos}\,\delta\, \text{Sin}\,\omega_s + \frac{2\pi\omega_s}{360}\, \text{Sin}\,\phi\, \text{Sin}\,\delta\right) \quad (1)$$

Where

I_{sc}-solar constant, n-day of the year, ϕ -latitude of the location, δ-solar declination, ω_s-hour angle

Using the extra-terrestrial radiation for the locations, the two ratios clearness index (H_g/H_0) and cloudiness index (H_d/H_g) has been found.

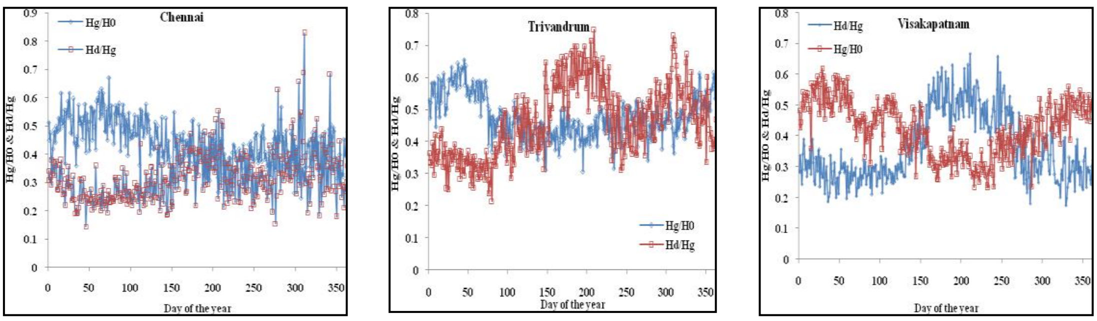
3. Results and Discussion

3.1 Variation of clearness and cloudiness index

Daily average clearness and cloudiness index for the three locations have been calculated by using measured daily average global and diffuse solar radiation and depicted in figs. 1 a-c. From the fig.1(a) , it is observed that, the clearness index at Chennai during the months from January to May is higher than the cloudiness index due to clear sky and extreme hot climate. The solar radiation from the sun reaches the horizontal surface without scattering in the respective location from January to May reflecting the characteristics of coastal area in South India. The clearness index slowly decreases and it seems to be equal to that of the cloudiness index at the starting of June. From the month June to December, the clearness and cloudiness index at Chennai are almost has same trend due to the hazy climatic condition. The haziness is accompanied with rain during June to August with high humidity. This led to the similar trend for both clearness and cloudiness index. Though the clearness index decreases after the month of May, the climatic condition at Chennai led to the suitability of utilizing solar thermal devices for domestic and industrial applications for all the day of the year.

Fig. 1 (b) shows the variation of clearness and cloudiness index at Trivandrum for all the days of the year. In Trivandrum, the clearness index is higher during the first three months of the year showing the clarity of the sky to allow the solar radiation to reach the surface without scattering. Thereafter the clearness index decreases for the next two months because of high humidity which led to the increase of cloudiness index. The humidity is accompanied with some amount of rain the location resulting in the decrease of clearness index. After the month of May, North east monsoon starts and both the indices are nearly equal and sum of the indices is unity. The linearity of the two indices is clearly interpreted.

Visakapatnam being hot and humid, from fig. 1 (c) it is observed that the clearness index is higher than the cloudiness index during the months from January to May. After May, the cloudiness index increases for next three months due to the monsoon leading to moderate amount of rainfall in the location. Both the indices are comparable for another 90 days from September as the climatic condition is partly cloudy. Followed by the cloudy sky, the remaining number of days of the year has clear sky condition leading to the domination of clearness index over cloudiness index.



(a) **(b)** **(c)**

Variation of clearness and cloudiness index at Fig.1 (a) Chennai (b) Trivandrum c) Visakapatnam

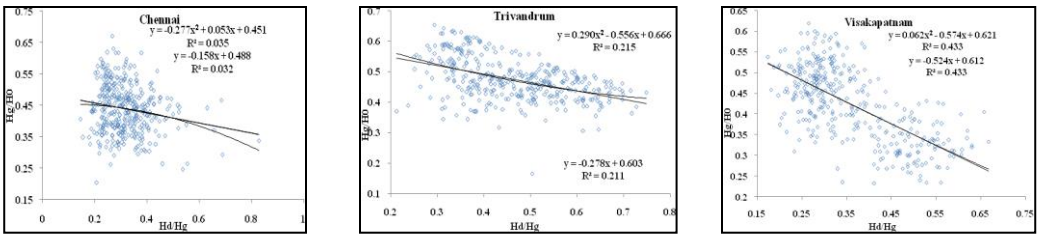
3.2 Correlation equation for clearness index

Since the clearness index is an important parameter for designing and performance testing of solar systems (Photovoltaic and Thermal), it is indispensable to correlate the clearness index with the cloudiness index in order to find the correlation equation for clearness index in terms of cloudiness index. The clearness index for all the three locations are plotted against the cloudiness index and trendlines have been drawn to find the linear and polynomial correlation equation for clearness index in terms of cloudiness index. Fig 2(a-c) represents the variation of clearness index with respect to the cloudiness index for the three locations. Table. 2 presents the linear and polynomial equations for clearness index in terms of cloudiness index by drawing the trendlines.

Table. 2 Linear and polynomial equations for Chennai, Trivandrum and Visakapatnam

S.No	Location	Linear Equation	Polynomial Equation
1.	Chennai	$H_g/H_0 = -0.158\ (H_d/H_g) + 0.488$	$H_g/H_0 = -0.277\ (H_d/H_g)^2 + 0.053\ (H_d/H_g) + 0.451$
2.	Trivandrum	$H_g/H_0 = -0.278\ (H_d/H_g) + 0.603$	$H_g/H_0 = 0.290\ (H_d/H_g)^2 - 0.556\ (H_d/H_g) + 0.666$
3.	Visakapatnam	$H_g/H_0 = -0.524\ (H_d/H_g) + 0.612$	$H_g/H_0 = 0.062\ (H_d/H_g)^2 - 0.574\ (H_d/H_g) + 0.621$

The correlation equations (linear and polynomial) for clearness index at Chennai, Trivandrum and Visakapatnam have given R^2 value and represented in tab. 3. For all the three locations, the polynomial equation shows higher R^2 compared to the linear correlation equation. The results clearly showed the significance of polynomial and linear correlation equation for the evaluation of clearness index in the absence of measured data of global solar radiation. Analyzing the data of Chennai, Trivandrum and Visakapatnam, the R^2 value for both linear and polynomial equations are comparable and can be utilized.



(a) **(b)** **(c)**

fig. 2 Linear and polynomial trendline for clearness index in terms of cloudiness index at a) Chennai b) Trivandrum c) Visakapatnam

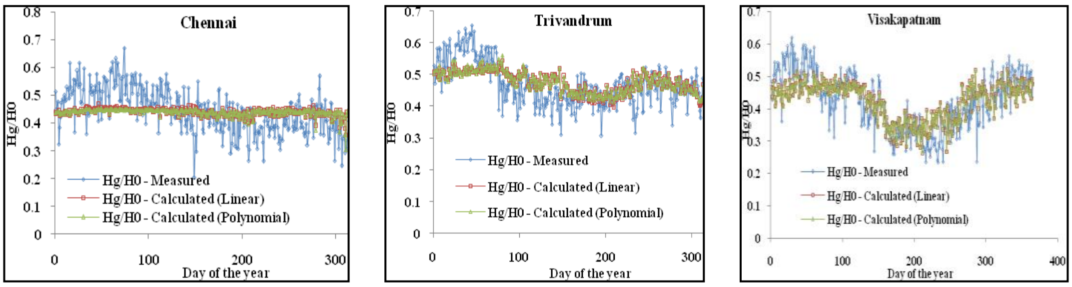
Table. 3 R^2 value for the linear and polynomial equations

Location	R^2 Value	
	Polynomial	Linear
Chennai	0.035	0.032
Trivandrum	0.215	0.211
Visakapatnam	0.433	0.433

3.2 Validation of the correlation equation

To validate the linear and polynomial correlation equation for clearness index in terms of cloudiness index for Chennai, Trivandrum and Visakapatnam, equations have been used to find the clearness index for all the days of the year and depicted in figs. 3(a-c). To compare the measured and calculated values of clearness index by using derived linear and polynomial correlation equations, percentage of standard deviation has been found. For Chennai, percentage of standard deviation between measured and calculated values of clearness index are found to be 4.45% and 3.64% respectively for linear and polynomial equation. Since the percentage of deviation is less than 5%, the equation can be used to find the clearness index for the respective location in the absence of global solar radiation data and also be utilized to find the clearness index of nearby location having same climatic condition.

Validation of the correlation equation for Trivandrum has been done and it has been found that for both the linear and polynomial equation, the percentage of standard deviation between measured and calculated values are reasonably agreeing with each other with least error. For linear equation it is found to be 3.39 and 2.77% for polynomial equation. Therefore it is concluded that the equation can be used for the locations nearer to Visakapatnam where measuring devices are not available. In the similar way, the percentage of standard deviation between measured and calculated values of clearness index are found to be 3.76 and 3.07% for linear and polynomial equations respectively. From the validation of the equations for three locations, it is shown that the percentage of standard deviation between measured and calculated values of clearness index is lesser than 5% on average.



(a) **(b)** **(c)**

fig. 3 Variation of measured and calculated clearness index (Linear and Polynomial) at a) Chennai b) Trivandrum c) Visakapatnam

Performance Statistics

The predictive accuracy of the proposed clearness index model was noted by calculating the mean bias error (*MBE*), root mean square error (*RMSE*), mean percentage error (*MPE*) and absolute mean bias error (*AMBE*). These are defined below:

Root Mean Square Error (RMSE)

The *RMSE* is defined as

$$\mathrm{RMSE} = \left[\frac{1}{n} \sum_{j=1}^{n} d_j^{\,2} \right]$$

where, d_j is the difference between the j^{th} calculated and j^{th} measured value of global radiation on a horizontal surface and n is the number of data pairs.

Mean Bias Error (MBE)

The *MBE* is defined as

$$\mathrm{MBE} = \left[\frac{1}{n} \sum_{j=1}^{n} d_j \right]$$

This test provides information with respect to overestimation or underestimation. The smaller the absolute value, the performance of the model becomes better. A positive value of the *MBE* gives the average amount of overestimation in the calculated values and vice versa. One drawback of this test is that overestimation of an individual observation will cancel any under estimation in other observations.

Mean Percentage Error (MPE)

MPE is defined as

$$\mathrm{MPE} = \frac{1}{n} \left[\sum_{j=1}^{n} \frac{|d_j|}{\overline{\overline{H}}_m} x100 \right]$$

For calculating the *MPE* values, the signs of the errors are neglected and the percentage errors are added to calculate the mean.

Absolute Mean Bias Error (AMBE)

This gives the value of absolute mean deviation between calculated and measured values of global radiation and is also a measure of the goodness of each correlation.

$$\text{AMBE} = \left[\frac{1}{n} \sum_{j=1}^{n} \left| d_j \right| \right]$$

Performance was assessed in terms of MPE, MBE, RMSE and AMBE. These indices were calculated for each month and year for Chennai, Trivandrum and Visakapatnam and expressed in absolute units, MJ /m^2 day. Proper computer programs were written in C language for the regression analysis for calculating the extraterrestrial radiation values H_0 and the day length S_0 using the standard procedure given by Duffie and Beckman (1991). The performance was calculated for each month of the year. Table. 3-5 presents the value of H_g calculated from the polynomial equation and compared with measured value in terms of different errors for Chennai, Trivandrum and Visakapatnam.

Table. 3 H_g calculated from the polynomial equation and compared with measured value in terms of different errors for Chennai

Month	$H_{g, cal}$	MPE (%)	MBE (MJ/m^2)	RMSE (MJ/m^2)	AMBE (MJ/m^2)
Jan	17.912	4.239	0.728	0.531	0.728
Feb	21.021	0.598	-0.127	0.016	0.127
Mar	22.062	4.042	-0.929	0.863	0.929
Apr	23.051	1.287	-0.301	0.090	0.301
May	22.662	0.661	0.149	0.022	0.149
Jun	20.946	2.443	-0.525	0.275	0.525
Jul	20.194	1.445	-0.296	0.088	0.296
Aug	20.405	1.714	-0.356	0.127	0.356
Sep	19.977	2.713	-0.557	0.310	0.557
Oct	18.660	0.787	0.146	0.021	0.146
Nov	16.532	3.887	0.618	0.383	0.618
Dec	17.080	7.646	1.213	1.472	1.213
Average	20.0418	2.622	-0.020	0.350	0.495

A verification of the present model was done by comparing it with existing local correlation. The local correlation was selected according to the availability of either city wise (correlation corresponds to the particular city) or region-wise (city corresponds to the particular region) for the city correlation. Table. 6 gives the list of selected models for verification with the proposed model.

It is seen that the proposed polynomial model has *MPE* of 1.24 (Chennai), 0.928 (Trivandrum) and 1.25 (Visakapatnam) whereas all other existing models gave higher errors, with a minimum of 2.85 (Chennai), 2.70 (Trivandrum) and 2.945 (Visakapatnam) [Modi and Sukhatrne (1979)] and a maximum of 9.71 (Chennai), 7.806 (Trivandrum) and 8.989 (Visakapatnam) [Mani and Rangarajan (1982)]. The above test clearly shows that the proposed model is better than the other models and also closely agrees with measured data.

Table. 4 H_g calculated from the polynomial equation and compared with measured value in terms of different errors for Trivandrum

Month	$H_{g, cal}$	MPE (%)	MBE (MJ/m^2)	RMSE (MJ/m^2)	AMBE (MJ/m^2)
Jan	17.686	2.925	0.503	0.253	0.503
Feb	21.476	1.557	0.329	0.108	0.329
Mar	22.056	4.068	-0.935	0.875	0.935
Apr	23.032	1.369	-0.320	0.102	0.320
May	22.450	0.284	-0.064	0.004	0.064
Jun	20.731	3.445	-0.740	0.547	0.740
Jul	20.320	0.826	-0.169	0.029	0.169
Aug	20.416	1.658	-0.344	0.118	0.344
Sep	19.914	3.021	-0.620	0.385	0.620
Oct	18.562	0.256	0.047	0.002	0.047
Nov	16.692	4.890	0.778	0.606	0.778
Dec	16.827	6.051	0.960	0.922	0.960
Average	20.013	2.529	-0.048	0.329	0.484

Table. 5 H_g calculated from the polynomial equation and compared with measured value in terms of different errors for Visakapatnam

Month	$H_{g, cal}$	MPE (%)	MBE (MJ/m^2)	RMSE (MJ/m^2)	AMBE (MJ/m^2)
Jan	17.825	3.735	0.642	0.412	0.642
Feb	21.159	0.057	0.012	0.000	0.012
Mar	21.940	4.571	-1.051	1.104	1.051
Apr	22.884	2.003	-0.468	0.219	0.468
May	22.793	1.242	0.280	0.078	0.280
Jun	20.804	3.107	-0.667	0.445	0.667
Jul	19.993	2.426	-0.497	0.247	0.497

Aug	20.415	1.665	-0.346	0.120	0.346
Sep	19.806	3.548	-0.729	0.531	0.729
Oct	18.450	0.350	-0.065	0.004	0.065
Nov	16.580	4.186	0.666	0.444	0.666
Dec	16.987	7.060	1.120	1.255	1.120
Average	19.970	2.829	-0.092	0.405	0.545

Table. 6 List of selected models and their references for verification of the proposed model

Reference	*a*	*b*
Mooley (1962)	0.300	0.460
Modi and Sukhatrne (1979)	0.300	0.440
Mani and Rangarajan (1982)	0.242	0.436
Veeran and Kumar (1993)	0.340	0.320

Table. 7- 9 shows the performance statistics of the selected models in terms of average value for Chennai, Trivandrum and Visakapatnam.

Table. 7 Performance statistics of the selected models in terms of average values

Reference	$H_{g, cal}$ Chennai	MPE (%)	MBE (MJ/m^2)	RMSE MJ/m^2)	AMBE (MJ/m^2)
Mooley [16]	20.633	3.343	0.572	0.693	0.613
Modi and Sukhatrne [17]	20.195	2.849	0.133	0.393	0.534
Mani and Rangarajan [18]	18.068	9.705	-1.994	4.566	1.994
Veeran and Kumar [19]	18.970	5.386	-1.091	1.668	1.138
Proposed Model	20.0418	1.238	0.044	0.116	0.252

Table. 8 Performance statistics of the selected models in terms of average values

Reference	$H_{g, cal}$ Trivandrum	MPE (%)	MBE (MJ/m^2)	RMSE MJ/m^2)	AMBE (MJ/m^2)
Mooley [16]	19.855	2.828	0.422	0.599	0.592
Modi and Sukhatrne [17]	21.526	2.695	0.201	0.328	0.429
Mani and Rangarajan [18]	17.589	7.806	-1.784	4.326	1.728
Veeran and Kumar [19]	18.362	4.956	-1.652	1.598	1.095
Proposed Model	20.013	0.928	0.052	0.162	0.238

Table. 9 Performance statistics of the selected models in terms of average values

Reference	$H_{g, cal}$ Visakapatnam	MPE (%)	MBE (MJ/m^2)	RMSE MJ/m^2)	AMBE (MJ/m^2)
Mooley [16]	21.536	2.968	0.622	0.786	0.715
Modi and Sukhatrne [17]	19.936	2.945	0.147	0.422	0.568
Mani and Rangarajan [18]	17.936	8.989	-1.856	3.957	1.897
Veeran and Kumar [19]	18.265	5.124	-1.154	1.428	1.202
Proposed Model	19.970	1.247	0.035	0.101	0.198

Conclusions

The linear and polynomial correlation equation for clearness index in terms of cloudiness index for South Indian locations (Chennai, Trivandrum and Visakapatnam) has been derived and validated to verify the reliability of the method adopted. It is seen that the error in calculated daily average clearness index values for the locations are within 5% of the measured values. Hence, the proposed correlation can be extended to other locations in South India that have similar humid-warm weather. Moreover, the analyzation of clearness index in the locations led to the conclusion that the best performance of solar collector of photovoltaic systems can be achieved in the locations and also for large scale installations. Further, the above linear and polynomial equation for clearness index regarding Chennai, Trivandrum and Visakapatnam can be applied for other near by locations.

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