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Prediction of daily global solar radiation using different empirical models at eastern subtropical region, Nepal

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Abstract

The current study estimates the daily global solar radiation (GSR) at subtropical region of eastern Nepal at Biratnagar Airport (lat. 26°28'53"N, long. 87°15'50"E and Alt. 72m) for 2016 using measured GSR values and meteorological parameters from 2015. The maximum of measured GSR of magnitude 15.9 MJ/m^2/day was found in April while the minimum of magnitude 8.7 MJ/m^2/day was found in January. Meteorological parameters such as the temperature and their relation with the GSR were utilized for this comparative study. Temperature-based multi-variable linear empirical models were used to perform regression analysis and determine the regression coefficients. The calculated regression coefficients from these models were utilized to predict the GSR values for subsequent year. The variation in the GSR estimated from these models were compared. Variation between measured GSR and estimated GSR for 2015 was also studied for each of these models. Performance comparison of these models was carried out by employing mean bias error (MBE), relative root mean square error (RRMSE) and adjusted coefficient of determination (R^2). Such study is relevant in situations where reliable data for sunshine duration is not adequately available. The Falayi model has the highest adjusted R^2 value of 0.61 but the largest MBE of 14.1%. The Garcia model has least adjusted R^2 value of 0.55 but least MBE of 6.6%. Both the Garcia and Chen and Li model predict similar GSR value of 12.8 and 12.5 MJ/m^2/day.

Keywords: Temperature model, empirical model, global solar radiation, GSR, regression technique.

Introduction

In recent years, modernization and urbanization has changed the outlook of the entire world. Modernization and urbanization gave rise to the global issue sprimarily regarding ambient air pollution and global warming due to heavy reliance on traditional energy sources[1]. The energy consumption pattern of Nepal indicates its disproportionate dependence on conventional and traditional fuels[2]. However, in recent years, clean and in-exhaustible solar energy has been gaining more and more attention. Global solar radiation (GSR) is a critical variable for estimating optimum operational capacity of solar furnaces, passive solar design, solar collectors and photovoltaic cells. Different methods utilizing different types of data could be employed to estimate any region's GSR. Major method includes the model employing neural network[3,4], empirical relationship[5,6], stochastic algorithm[7] and geostationary satellite images[8]. Applicability of these models in estimating solar radiation have been examined at various locations. Among these methods, the empirical method utilizing meteorological data is the most examined and widely used method because of the availability of reliable data and simplicity[5,6,9].

In Nepal, financial and technical limitations have restricted the establishment of meteorological stations all over the country. Only 284 meteorological stations (either climatological or precipitation) are in operation, out of which only 64 are capable of measuring Solar Radiation while only 34 of them have the necessary infrastructure installed for the measurement of Sunshine Duration[10]. Since, the data of sunshine is not adequately available for many different regions, solar radiation can be estimated using various climatic variables.

Since last few decades or so, numerous models employing meteorological parameters have been developed, analyzed and evaluated to accurately estimate GSR[6]. Angstrom pioneered this domain by employing a linear model[11]. Prescott modified the Angstrom model by introducing extraterrestrial solar radiation (H_0)[11]. Angstrom Prescott (A-P) model, because it is simple and strongly correlated to sunshine duration, is vastly employed to estimate global radiation[12–15]. Since the establishment of A-P model, several modifications have been made in order to improve the estimation by adding one or more parameters of meteorology like ambient temperature, precipitation, wind velocity, and so on[11]. Despotovic conducted a detailed review of various sunshine-based model and performed statistical analysis to evaluate the performance of an individual model[16].

Strong correlation of sunshine duration with solar radiation ensures that sunshine-based models perform more efficient[17–19] but all-round application of these models is restricted because of the high initial investment required for the sunshine duration measuring instrument. This restriction is more pronounced in developing countries like Nepal because of which accurate sunshine duration data are not readily available. In contrast, ambient temperature range is a readily available parameter. Hargreaves and Samani[20] developed a simple equation (H-S model) incorporating mean monthly temperatures as the input to predict solar radiation. Since then, several modifications have been made in order to improve the estimation by adding other meteorological parameters. Hassan et al., then, modified H-S model with the introduction of precipitation term that outperformed two of these most effective sunshine duration based models from literature[21]. Similarly, Li et al. introduced relative humidity into the H-S model[22]. Although all of the temperature-based models were derived empirically, these models were based on the assumption that ambient temperature and solar radiation were strongly correlated[23]. However, the performance of temperature-based model is found to vary according to the geographical location and local climate[24].

Two important aspect of the work includes; i. the estimation of daily GSR employing meteorological data which were readily available; ii. the applicability and accuracy evaluation of three different models available in the literature to predict daily GSR.

The result of the study might assist in selection of appropriate temperature model for estimating daily GSR values at locations where daily sunshine duration measurements are not in adequacy.

Methodology

Data pertaining to daily GSR, temperature and daily sunshine duration for Biratnagar were obtained from the Department of Hydrology and meteorology (DHM), Government of Nepal. Linear piecewise interpolation was employed in MATLAB R2018a for the missing values of the measured meteorological parameters. The plots were obtained from Microsoft Excel 2013.

Solar radiation: Daily GSR at Biratnagar was measured employing CMP6 Pyranometer manufactured by Campbell Scientific, Inc. This instrument registers solar irradiance in W/m^2. This pyranometer houses a blackened thermopile underneath two glass domes. The thermopile sensor generates a signal in the order of millivolts which is proportional to the heat generated by the solar radiation. The solar radiation is read directly from the data logger.

Sunshine Hours: The Campbell-Stokes sunshine recorder is employed for the measurement of sunshine duration which basically utilizes sunshine cards placed in grooves in the bowl to measure sunshine duration. In a spherical bowl is concentrically mounted a spherical glass and it leaves burn pattern on the sunshine card.

Temperature: The data pertaining to both maximum and minimum daily temperatures were required for the models used in this study. The maximum daily temperatures were measured using mercury thermometer whereas, the minimum daily temperatures were measured using alcohol thermometer owing to lower freezing point of alcohol than that of the mercury.

Empirical Models: The following models were utilized for the prediction of the daily GSR in Biratnagar: Falayi model, Garcia model and Chen and Li model.

Falayi[25] developed 12 different multi-variable linear regression models for predicting the correlation between GSR and meteorological parameter for Iseyin, Nigeria. One of his models employing mean ambient temperature and ratio of maximum ambient temperature to minimum ambient temperature is taken for the study. It is used to predict Hg values of 2015 but due to limited reliable sunshine hour data for 2016, it wasn't utilized for predicting GSR for corresponding year.

$$\frac{H_g}{H_0} = a + b_1 \frac{n}{N} + c_1 T + c_2 \frac{T_{min}}{T_{max}} \quad (1)$$

Garcia[26] developed several models basically employing the ratio of temperature difference to the potential sunshine duration in various combinations. The simplest linear model employing this ratio is taken for the study.

$$\frac{H_g}{H_0} = a + b_1 \left(\frac{\Delta T}{N}\right) \quad (2)$$

Where, ΔT denotes the difference between maximum ambient temperature and minimum ambient temperature i.e.,$\Delta T = T_{max} - T_{min}$, a and b_1 represent empirical constants.

Chen and Li[27] developed 20 different models to estimate GSR from meteorological data. One of his models employing maximum ambient temperature and minimum ambient temperature is taken for the study.

$$\frac{H_g}{H_0} = a + c_1 T_{max} + c_2 T_{min} + c_3 T_{max} \times T_{min} \quad (3)$$

Where, T_{max} and T_{min} denote maximum temperature and minimum temperature, respectively, in any given day, and a, c_1, c_2 and c_3 are empirical constants.

To predict the GSR, denoted by H_g which is measured in MJ/m^2/Day, first H_0 i.e., extra-terrestrial GSR needs to be computed utilizing the equation[28]:

$$H_0 = \frac{24}{\pi} H_{sc} \left(1 + 0.033 \cos\frac{360n}{365}\right)\left(\cos\phi \cos\delta \sin\omega_s + \omega_s \frac{\pi}{180} \sin\phi \sin\delta\right) \quad (4)$$

Where: φ denotes latitude (rad), δ denotes solar declination angle (rad), ω denotes sunset hour angle, and n denotes day of the year.
The solar declination angle can be obtained by employing the equation[29]:

$$\delta=23.45\sin\left(\frac{360}{365}(284+n)\right) \quad (5)$$

Day length can be calculated as

$$N=\frac{2}{15}\cos^{-1}(-\tan\phi\tan\delta) \quad (1)$$

Calculation of sunset hour angle is done using equation

$$\omega=\cos^{-1}(-\tan\phi\tan\delta) \quad (2)$$

Results and discussion

Statistical parameters viz. adjusted coefficient of determination (R^2), Mean bias error (MBE) and relative root mean square error (RRMSE) were determined to compare the performance of these models. The values of statistical parameters are listed in Table-1. Adjusted R^2 was used because the models depend on multiple variables. Each model was subjected to multiple variable linear regression.

The empirical constants were estimated from Garcia[26] model are a = 0.158 and b_1 = 0.262. The regression constants were also estimated from Chen and Li[27] model are a = -0.113, c_1 = 0.036, c_2 = -0.029 and insignificant c_2 of 2.8E-06. Falayi[25] model results the empirical constants to be a = 0.518, b_1 = 0.115, c_1= 0.017 and c_2 = -0.960. The values of regression constants from both were employed to predict the GSR at the same geographical location for proceeding year and comparison between both these estimates were made.

Table-1: Statistical Tools and Error Analysis of different models.

Model	Falayi	Garcia	Chen and Li
RMSE	22.6 %	24.5 %	23.1 %
MBE	14.1 %	6.6 %	11.7 %
Adjusted R^2	0.61	0.55	0.60

Comparative study of the measured GSR with the predicted GSR for year 2015 for aforementioned models are shown in subsequent figures. The relation between average temperature and measured GSR is also shown. Prediction for GSR of 2015 were carried out using all three models. The GSR for the subsequent year 2016 is predicted using Garcia and Chen and Li models, due to limited availability of reliable sunshine hour data for 2016 needed to utilize Falayi model. Daily GSR values were predicted but the Hg values used in the subsequent plots are the monthly averages.

The measured GSR has a maximum value in April, 15.9 MJ/m^2/day, which can be observed by the peak in the graph. The minimum is observed to be in January. 8.7 MJ/m^2/day. The GSR seems to increase from January to April and starts to fall. The second peak on October could be observed, which could be mainly due to reduction in monsoon and clear sky. The average temperature increases from January until July, from when it starts to fall. This shows the variation in measured GSR is not only due to temperature but there could be other meteorological parameters responsible for it.

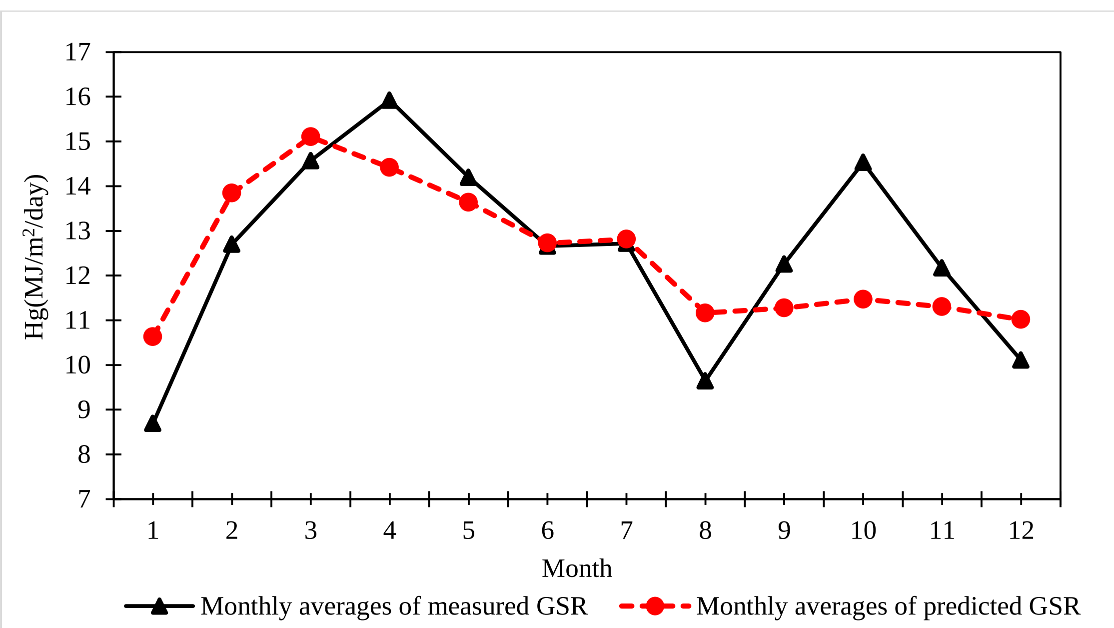

Figure-1: Comparison study at Biratnagar for the year 2015 using Garcia model.

Figure-1 indicates the relation between measured GSR and predicted GSR for Garcia model for 2015. The model fails to capture the sharp variations in the measured values of GSR but captures the overall trend of measured GSR fairly accurately. This statement is complemented by the fact the adjusted R-square value for Garcia model is lower than other two and this model also has higher RRMSE value. The lack of variation results in its MBE value being lower. The model predicts GSR which is minimum in January, maximum in March and fairly constant from August to December.

Figure-2 indicates higher similarity between the measured values of GSR and values predicted using Chen and Li model for 2015. The reason for this relationship could be that Chen and Li model employed multiple forms of temperature variables than Garcia model. It has a higher coefficient of determination than for Garcia model and lower RRMSE value. It captures the variation in measured GSR much accurately than Garcia model. This could be observed at the global minimum in January, the local minimum in August and a slight increase in GSR value in October.

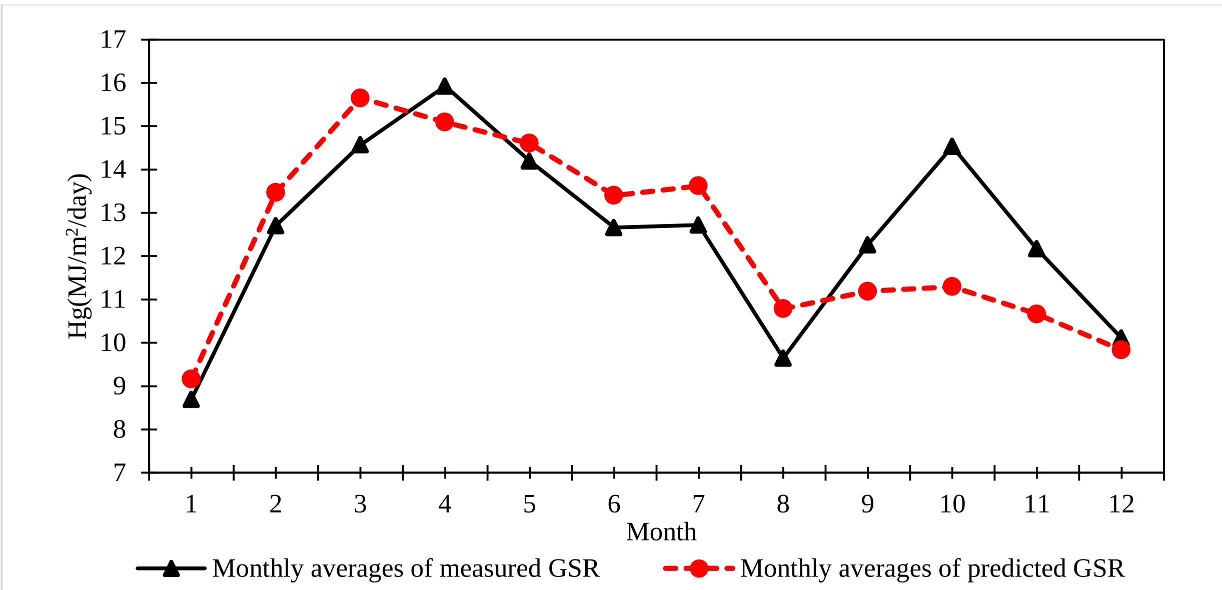

Figure-2: Comparison study at Biratnagar for the year 2015 using Chen and Li model.

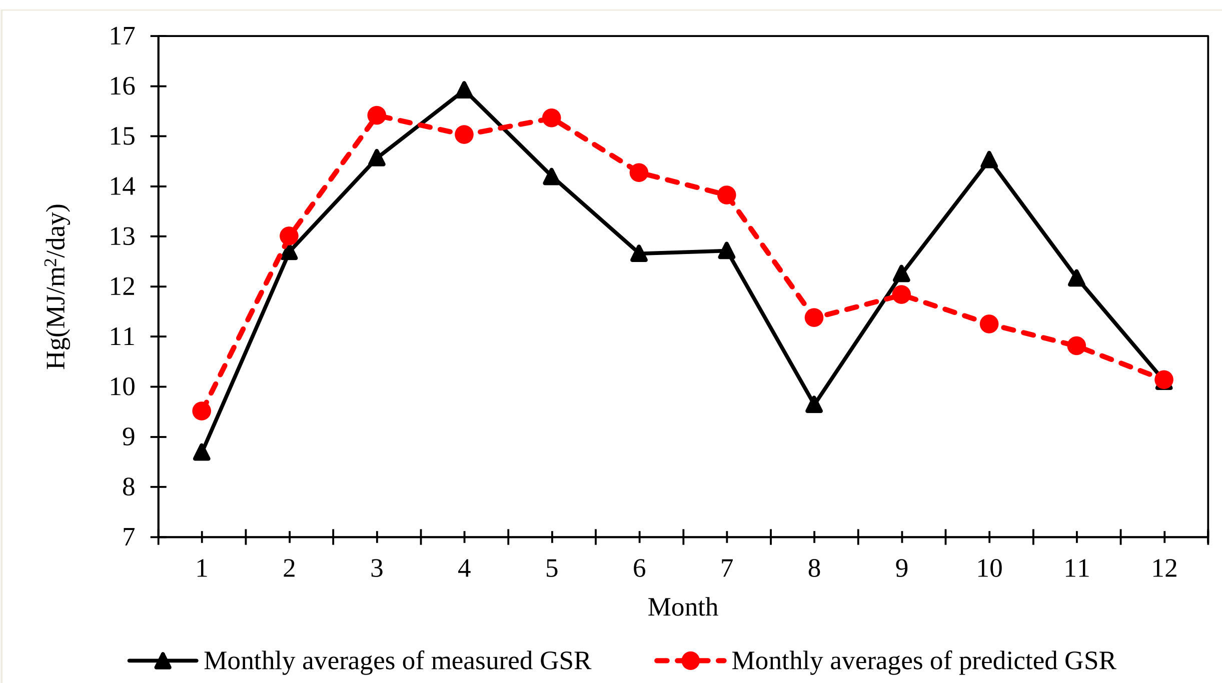

Figure-3: Comparison study at Biratnagar for the year 2015 using Falayi model.

The relationship between measured values of GSR and predicted values GSR using Falayi model can be observed in Figure-3. The model captures the overall trend but not as closely as in the case of Chen and Li model despite the fact that it employed the sunshine hour, day length and temperature parameters. The maximum is observed in March instead of April and the local minimum in August could not be speculated. Hence, from these observations, we can state Chen and Li model gives fairly accurate prediction of GSR, among, the three for this particular geographical location in these years and nearby few.

The GSR for the year 2016 is predicted using Chen and Li model and Garcia model. Although the overall trend is fairly similar, some significant difference could be observed between the two. Chen and Li model give much lower GSR value for January than Garcia model does. But, the prediction by Garcia model provides much varying values which can be observed through various peaks. Significant difference could be observed for the month of July and November. However, both models predict similar GSR values for the month of March to May and from September to October. Further works needs to be carried out the see the accuracy of both of these predictions using measured GSR values of year 2016. Both the Garciaand Chen and Limodel predict similar GSR value of 12.8 and 12.5 MJ/m^2/day.

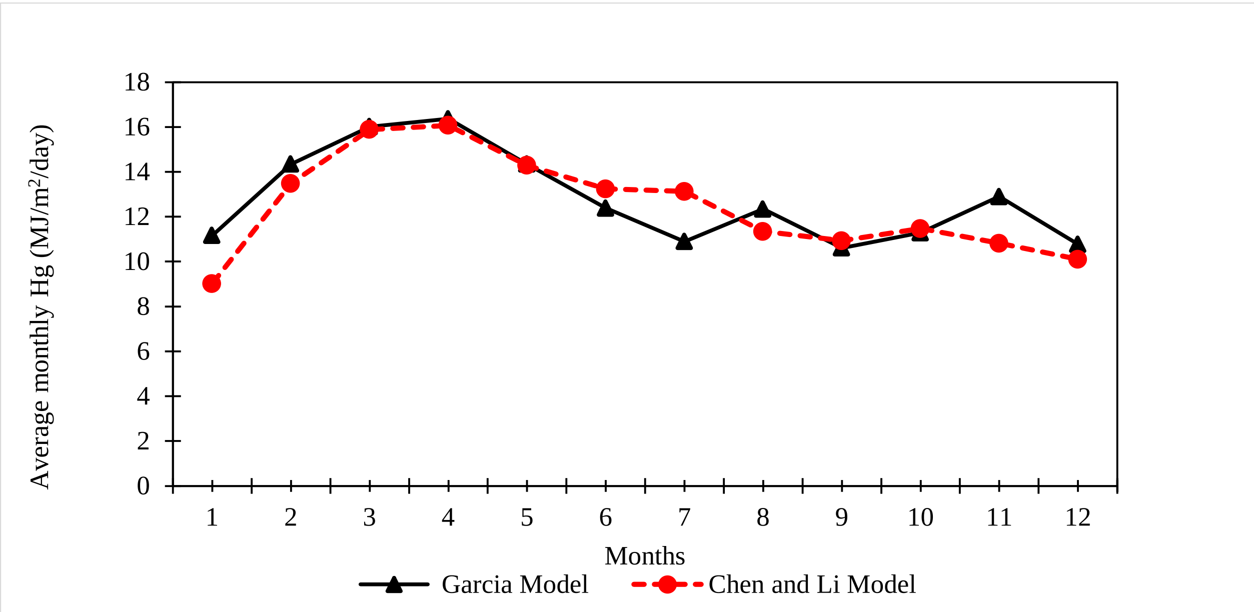

Figure-4: Comparison of average monthly GSR given by Garcia model and Chen and Li model for 2016 at Biratnagar.

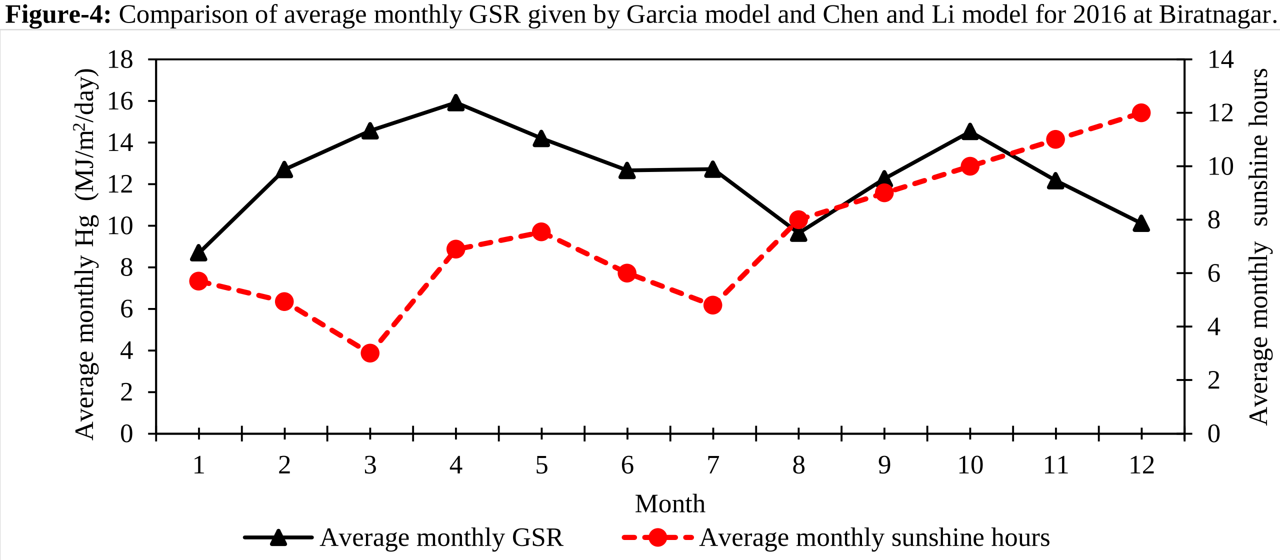

Figure-5: Comparison of the average monthly sunshine hours and GSR for the year 2015.

Figure-4 shows that the monthly averages of actual GSR and monthly averages of sunshine hours are consistent with each other. This is a consequence of the fact that there exists a positive correlation between GSR and sunshine duration i.e., the GSR increases with sunshine duration and vice versa. As can be seen in the Figure-5, here is a decrease in both sunshine duration and GSR during mid-year which can be attributed to the weather being cloudy during these months.

Figure-6 indicates that the average values of daily temperature and measured average GSR are positively correlated. It is an indication that days with high value of average GSR naturally have high average temperatures. From the curve showing the variation of GSR with the days of the year, it is clear that the GSR first gradually increases from January, reaches maximum in the month of June i.e., during mid-year, and then gradually falls during the latter half of the year.

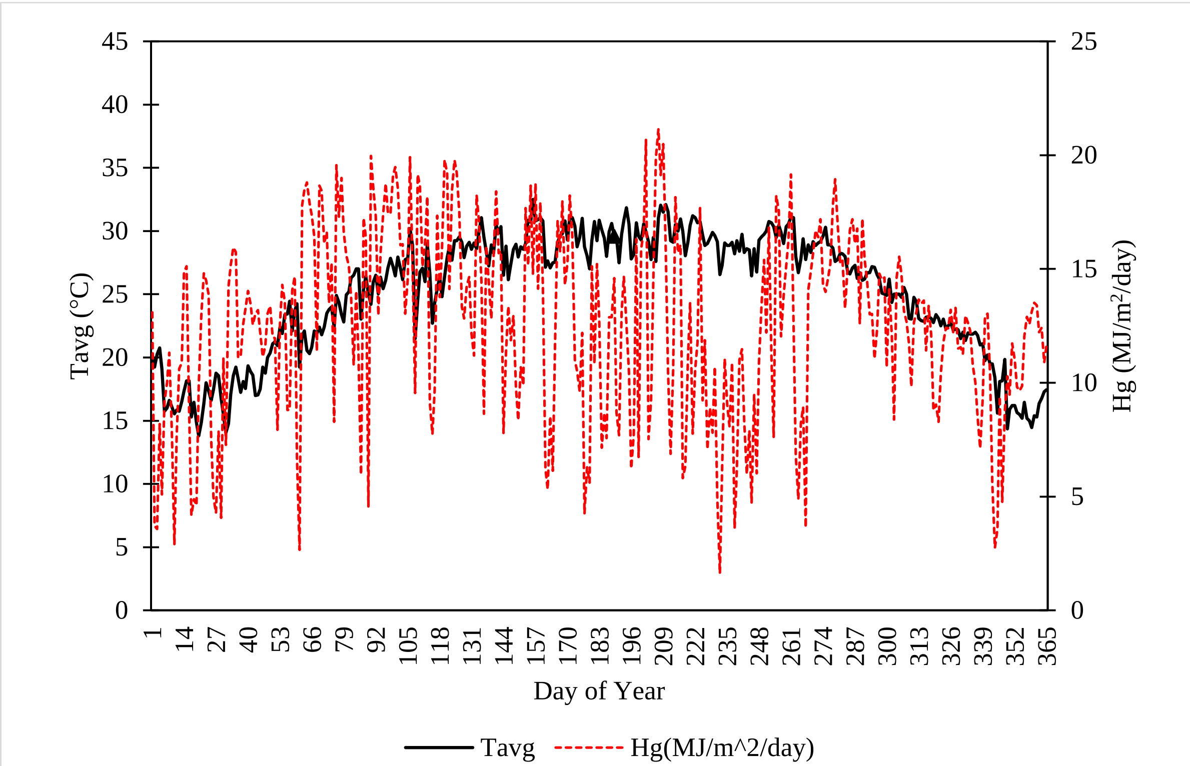

Figure-6: Comparison of average daily temperature and actual GSR for the year 2015.

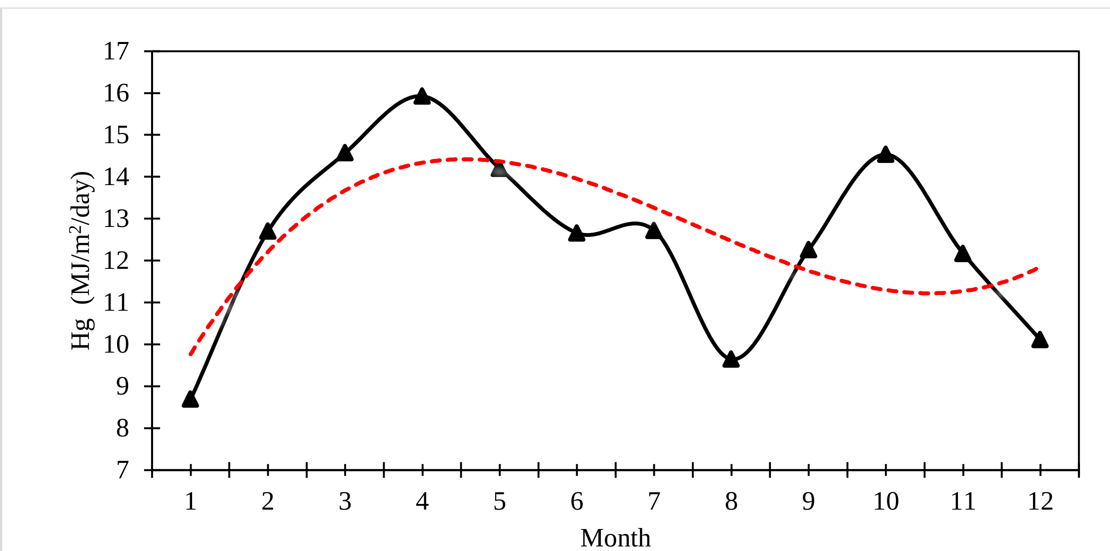

Figure-7: Monthly variation of measured GSR in the year 2015.

This is a consequence of the seasonal variation in the Northern Hemisphere due to the rotation of the year. Since the GSR directly affects the temperature at any location on the Earth, it is expected that the average daily temperature and average GSR follow similar trends. Nonetheless, it is seen that the average GSR is found to suddenly increase above and decrease below the expected values. Moreover, the GSR line is found to largely deviate from the trend of the average temperature. This unusual trend is speculated to have caused due to interpolation of the missing measured GSR values in the data of GSR for the year 2015.

Shown in Figure-7 is the monthly measured value of GSR for the year 2015 in Biratnagar. A third-degree polynomial trend line (dotted line) is fitted with monthly variation of measured GSR. The maximum value of GSR, as shown by the trend line, is observed for April, May, and June whereas the minimum is observed during for November and December. The trend line (dotted line) is of polynomial of order 3, which closely resembles the expected curve of showing variation of GSR over the year.

Figure-8 illustrates the seasonal variation of GSR for the year 2015 at Biratnagar Airport. The maximum GSR is observed in Spring while the minimum GSR is observed in Winter season. Both the Garciaand Chen and Limodel predict similar GSR value of 12.8 and 12.5 MJ/m^2/day.

Conclusion

The maximum of measured GSR of magnitude 15.9 MJ/m^2/day was found in April while the minimum of magnitude 8.7 MJ/m^2/day was found in January for the year 2015. This might be attributed to the season change and local weather conditions. Similarly, it was observed that temperature-based empirical models viz Chen and Li model, Garcia model and Falayi model fairly captured the variation in measured GSR, with Chen and Li model showing the strongest agreement among the three. The GSR for 2015 and 2016 was estimated using these models and their accuracy analyzed.

These models would be helpful in scenarios where reliable sunshine hour data are not available. The accuracy of their prediction of GSR in subsequent years could be further analyzed by comparing the prediction with measured values of GSR in the future. The deviation of these estimations from those that could be obtained from standard Angstrom Prescott model could also be analyzed in the future.

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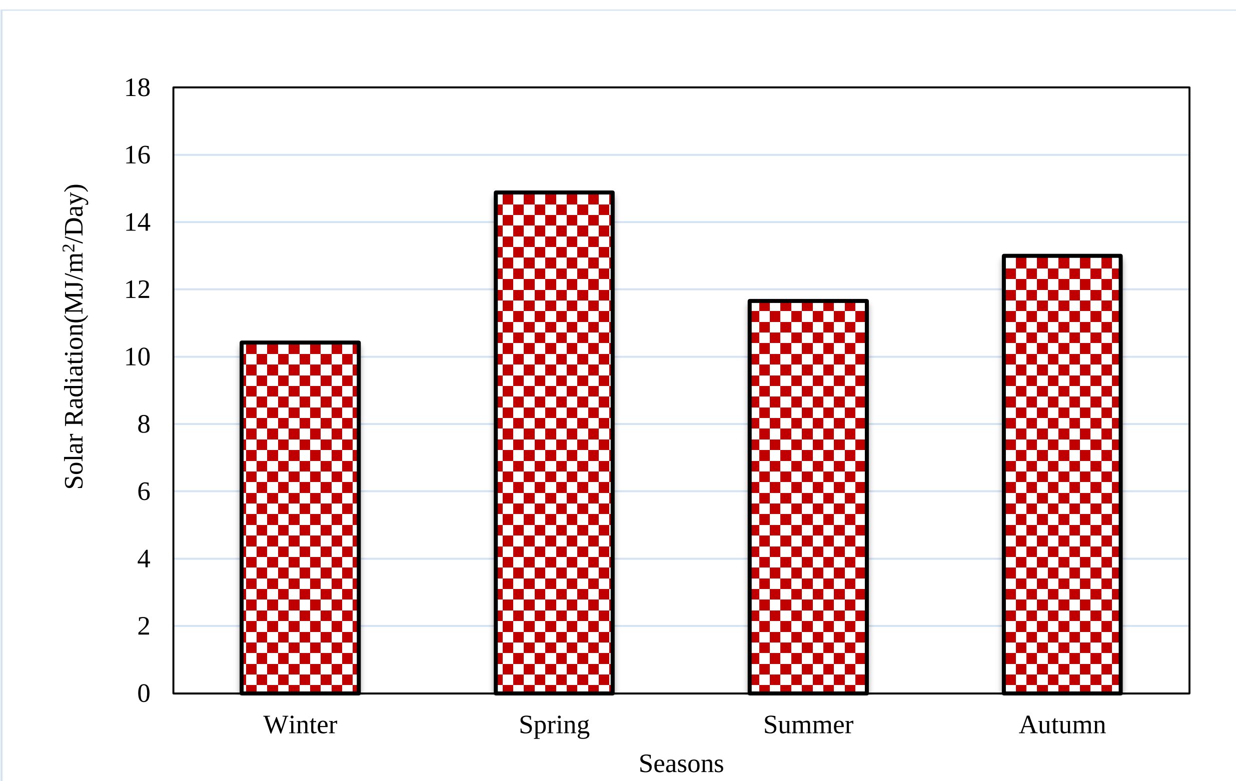

Figure-8: Seasonal Variation of daily GSR for 2015 at Biratnagar.

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