

Estimation of Global Solar Radiation from Temperature Extremes: A Case Study of Hebron City, Palestine

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Abstract: Solar radiation is the main energy source for mankind and an accurate data of solar radiation levels for a particular location is vital for the optimum operation of solar energy transducers such as photovoltaic cells and solar thermal collectors. This study aimed to calibrate some of the existing models in the literature for estimating daily global solar radiation parameter using available measured records of air temperature extremes and new models were developed based on maximum and minimum air temperatures. Applicability of the Hargreaves model, Allen model, Bristow-Campbell model and Chen et al. model were evaluated for computing the global solar radiation for Hebron city in Palestine. Estimated values were compared with measured values in terms of the coefficient of determination (R^2) and root mean square error (RMSE). All models provide good estimates when compared to the accurate values with R^2 0.9226 (Bristow-Campbell model) to 0.9547 (Chen et al. model), while the proposed model provides a value of 0.9632. The RMSE value ranges from 0.7632 for Chen et al. model to 0.9211 for Bristow-Campbell model, however a lower value (0.7118) for the proposed model. This study found that the proposed model estimates global solar radiation at the location of study better than the other models.

Keywords: Solar Radiation, Air Temperature Extremes, Model Comparison, Model Validation

1. Introduction

Solar radiation at the Earth's surface is the principal and fundamental energy for many physical, chemical and biological processes, such as crop growth and plant photosynthesis, and it is also an essential and important variable to many simulation models studies, such as agriculture, environment, hydrology, meteorology and ecology. Hence, an accurate record of solar radiation is of vital importance [1-2].

However, solar radiation data is not as readily available as air temperature and precipitation data [3-5]. Even at stations where solar radiation is observed there could be many days when solar radiation data are missing or lie outside the expected range due to equipment failure and other problems [6]. These problems could be one of many: calibration problems, problems with dirt on the sensor, accumulated water, shading of the sensor by masts, etc.

The demand for suitable radiation data has in turn led researchers to develop a number of predictive methods for estimating solar radiation. Some of these methods include

estimating solar radiation from other available meteorological observations [7-14]. However, those are based on empirical relationships using commonly measured meteorological elements such as air temperature data are attractive due to lower data requirement and computation costs [3, 15]. In addition, the temperature-based solar radiation model can reduce the uncertainty of the crop simulations [1, 11, 16-17].

Although air temperature-based empirical models are founded on theoretical concepts for energy exchange on the surface boundary layer [18]. These models are based on the assumptions that (a) clear skies will increase the daily maximum temperature because of the greater short wave radiation input, while resulting in decreased minimum air temperature due to reduced long wave emission from the atmosphere; and (b) cloudy conditions will decrease the daily maximum air temperature due to reduced air transmissivity, while resulting in increased minimum air temperature due to increased long wave radiation from the clouds [19-21]. Therefore, estimating solar radiation using air temperature data is of vital importance and significance.

Bristow and Campbell (1984) using this relationship estimated daily solar radiation using an exponential function of daily air temperature range (ΔT) [8]. They were able to account for the variation of the incoming daily solar radiation data at the site of interest. The Bristow and Campbell model has been modified by others for specific applications. For example, Donatelli and Marletto (1994) and Donatelli and Campbell (1998) included a summer night air temperature factor to improve underestimation of predicted values during the summer [22-23]; Hargreaves et al. (1985) also developed a simple linear relationship between daily air temperature range and clearness index [9]. Hunt et al. (1998), based on the evaluation of five solar radiation models, found best estimates in a model with multiple-linear relationship between daily incoming solar radiation, and air temperature and precipitation [1]. Mahmoud and Hubbard (2002) also found more stable estimations of daily incoming solar radiation from clear-sky solar radiation and daily air temperature range compared with the Bristow and Campbell model [24].

Therefore, the objective of this study is the validation of various models in the literature; mainly those use the difference between maximum, minimum and average air temperatures, to estimate daily total global radiation in Hebron city, Palestine. Also, this study suggests a new estimation model for the prediction of the solar radiation. This work is organized as follows: In section II i will discuss the methodology used, in section III provides the models used in this study, in section V the discussion of the results and finally section VI provides the conclusions.

2. Methodology

Site Study and Data

Hebron City is a busy hub of west bank trade located in the southern part of west bank in Palestine at latitude of $31^{\circ}57'$ N, it lies 950 meters above sea level and its climate is hot in summer and cold in winter. Also, it receives a large quantity of solar radiation, especially in summer [9]. The data employed in this work were supplied by the Palestinian meteorological office. A radiometric station was established at the Hebron city municipality (1000 m above sea level). The meteorological dataset is selected on a daily basis. These meteorological data belong to the period between January 2015 and December 2017. Maximum and minimum temperatures, daily total global solar radiation, and daily average temperature values were taken from meteorological station. Extraterrestrial solar radiation values were obtained by calculation. With the help of this data obtained from meteorological station, the models in the literature have been calibrated and new model have been developed.

Calculations of Daily Extraterrestrial Solar Radiation

The plane of rotation of the earth around the sun is called the ecliptic plane. The rotation axis of the earth is called polar axis. The earth's rotation and the position of the earth axis causes diurnal and seasonal changes in solar radiation. The angle between the sun and the equatorial plane of the earth is different in every day of the year. This angle is called the solar declination angle; δ [25]. The solar declination angle's mathematical formula can be seen in equation 1. J is the calendar day in this equation with J = 1 on January 1 and J = 365 (or 366 during leap years) on December 31 [26-28].

$$\sin \delta = 0.39785 * \sin[278.97 + 0.9856J + 1.9165 * \sin(356.6 + 0.9856J)] \quad (1)$$

Daily extraterrestrial solar radiation as provided by Iqbal (1983) as shown in equation 2.

$$H_0 = \frac{24}{\pi} * I_{sc} * E_0 * \sin \varphi * \sin \delta * \left[\left(\frac{\pi}{180} \right) * w_s - \tan w_s \right] \quad (2)$$

Where I_{sc} is the solar constant and it is equal to 4.921 MJ/day.m^2 [27], w_s is the sunrise hour angle (eq. 3), φ is the latitude of the site and E_0 (eq. 4) is the eccentricity correction factor of the earth's orbit.

$$w_s = \cos^{-1}(-\tan \varphi * \tan \delta) \quad (3)$$

$$E_0 = 1 + -0.033 * \cos \left(\frac{2\pi * J}{365} \right) \quad (4)$$

3. Model Description

Recent studies on temperature-based models in the literature [10, 14] assume that solar radiation is a function of the difference between daily maximum and minimum air temperature. This is based on the assumption that the difference generally indicates daily cloudiness. Clear skies corresponds to higher solar radiations levels at the earth surface and cloudy skies corresponds to lower solar radiation levels. The regression models proposed in the literature and used in this study as well as the proposed model are listed in Table 1.

Table 1. Regression models used in the study.

Model No.	Regression Equation	Source
1	$\frac{H}{H_0} = a * (T_{max} - T_{min})^{0.5} + b$	Hargreaves (1985)
2	$\frac{H}{H_0} = a * (T_{max} - T_{min})^{0.5}$	Allen (1997)
3	$\frac{H}{H_0} = a * [1 - \exp(-b\Delta T^c)]$	Bristow and Campbell (1984)
4	$\frac{H}{H_0} = a * \ln(T_{max} - T_{min}) + b$	Chen at al. (2014)
5	$\frac{H}{H_0} = a * \ln(T_{max} - T_{min}) + b \left(\frac{T_{min}}{T_{max}} \right)^2$	Proposed model

All models were used in this study considering the temperature extremes as the principle input in order to

estimate global solar radiation at the study site. However, the parameters and accuracy of these empirical formulas need to be calibrated and tested locally. The empirical coefficients for each model are obtained from the regression equation and then an assessment criteria was used to compare the results obtained.

4. Assessment Criteria

Most studies evaluating the performance of solar radiation models have traditionally used coefficient of determination (R^2), root mean square error (RMSE) and/or model bias to assess model suitability and comparison [1, 3, 24, 29-31]. The test on RMSE provides information on the short-term performance of the model as it follows a term-by term comparison of the actual deviation between calculated and measured value [17]. The test of MAPE provides information on the long term performance of the models studied. Also, the coefficient of determination was used to measure the relation between measured and estimated global solar

radiation.

5. Results and Discussion

For many developing countries solar radiation measurements are not easily available due to the incapability to afford the measuring equipment's and techniques involved. It is therefore important to consider methods of estimating the solar radiation based on the readily available meteorological parameters. In this work temperature extremes were used to evaluate the empirical formulas listed in table 1 in order to estimate global solar radiation in Hebron city, Palestine.

The regression constants a, b and c are reported for the four models in Table 2. The regression coefficient provides a valuable value for all models with slightly higher values for Chen et al. and the proposed models. The monthly values of RMSE and MAPE between measures and estimated global solar radiation data for the four models are calculated and presented in Table 3.

Table 2. Regression coefficients of the five models for Hebron city.

Model No.	R^2	a	b	c	Source
1	0.9324	0.1622	-0.0176	-	Hargreaves (1985)
2	0.9331	0.1384	-	-	Allen (1997)
3	0.9226	1.751	0.9416	0.0620	Bristow and Campbell (1984)
4	0.9547	0.3186	-0.1152	-	Chen et al. (2014)
5	0.9632	0.2314	0.04170	-	Proposed model

Table 3. The values of RMSE and MAPE of the five models.

Model No.	RMSE (MJ/m ² .day)	MAPE (%)	Source
1	0.8874	9.1145	Hargreaves (1985)
2	0.8225	8.3620	Allen (1997)
3	0.9211	9.4426	Bristow and Campbell (1984)
4	0.7632	0.6625	Chen et al. (2014)
5	0.7118	0.5080	Proposed model

The statistical validation presented in table 3 provides that best performance of the proposed model with RMSE value 0.7118 MJm⁻²day⁻¹ and MAPE value 0.5080, Chen et al. (2014) model provides a close values of RMSE and MAPE to the proposed model. The worst values were obtained for the model of Bristow and Campbell (1984). As a result, the proposed model was found to be more accurate than the other models used in this study to estimate global solar radiation by using air temperature extremes in Hebron city.

Table 4 presents the measured and calculated values of the monthly average of daily global solar radiation on a horizontal surface for Hebron city. It can be concluded that the calculated values from the five models are in a good

agreement with the measured data. However, Hargreaves (1985) provides an under estimation of the global solar radiation values, whereas Allen (1997), Bristow and Campbell (1984) and the proposed model provide an overestimation of global solar radiation values, while Chen et al. (2014) model provides an under estimation in summer months (May to September) and over estimation of the other months of the year. Overall, it was found that the proposed model provides more accurate estimates as compared with the measured global solar radiation in winter months (October to April) while Chen et al. (2014) model provides a closer estimated values to the measured in summer months.

Table 4. The comparison between measured and estimated values of the monthly average daily global solar radiation (MJ/m²) for the models.

Month	Measured	Hargreaves (1985)	Allen (1997)	Bristow and Campbell (1984)	Chen et al. (2014)	Proposed model
JAN	11.8271	11.6032	12.5234	12.9343	12.3072	12.0211
FEB	16.5234	15.4113	17.4617	17.0930	17.2306	16.9734
MAR	20.1504	19.6261	21.8422	21.4053	20.9850	20.6352
APR	25.1654	24.0842	26.2091	26.2119	25.7509	25.4094
MAY	29.8173	28.3320	30.4025	30.8225	29.4063	30.3046
JUN	30.9034	29.1268	32.0919	32.3233	30.5226	31.4461
JUL	31.0713	30.1901	32.9791	33.0861	30.0823	32.0318

Month	Measured	Hargreaves (1985)	Allen (1997)	Bristow and Campbell (1984)	Chen et al. (2014)	Proposed model
AUG	28.7423	27.7342	30.0563	29.9724	28.1532	29.9164
SEP	23.9841	22.2402	25.0984	24.9315	23.4205	24.7057
OCT	18.0949	17.1826	19.6132	19.3478	18.9521	18.6361
NOV	14.0923	13.0611	15.7328	15.5546	14.8381	14.5064
DEC	12.0553	11.2203	13.9117	13.7443	12.9066	12.4426

6. Conclusion

Empirical models are usable tools to estimate global solar radiation, if the radiation parameters are not available in the station. Main aim of this study is the estimation of the daily total solar global radiation values by using maximum and minimum daily air temperatures. Four models in the literature and a proposed model have been employed for estimating global solar radiation for Hebron city. The differences between the results of the different models are very clear in terms of R^2 and RMSE values. The proposed model is better than the other models according to R^2 and RMSE, and has the best performance based on the measured data at one station in Hebron city. It can be recommended to use the proposed equation.

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