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A Multilinear Model for Estimating the Monthly Global Solar Radiation in Qassim, Saudi Arabia

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Abstract

Information on the global solar radiation is essential for many solar energy applications. Because of the cost of the measuring equipment, data on global radiation are not always available in most places, especially in developing countries. To overcome this difficulty, several attempts have been made to estimate solar radiation components from easy-to-measure atmospheric and/or geographical variables. In this study, monthly mean global solar radiation data for Qassim City, Saudi Arabia for the period from 1971 to 1998 were modelled using three meteorological variables: relative humidity, air temperature and atmospheric pressure. The predictability of the model was superior to the experimental data, showing a correlation coefficient (R) of 0.988. The mean percentage error (MPE) was less than 1%, the root mean square error (RMSE) was 0.02 and the mean bias error (MBE) was -1.1×10^{-4}. The performance model was validated using an independent data set for the period between 2003 and 2005. The statistical results were optimal and showed the ability of the model to predict the monthly global solar radiation for Qassim City for any period of time with less error. The predictability of some of the previously proposed models, which differed from each other in terms of the variables that they used and the number of variables contained, were tested to estimate monthly global solar radiation. The performances of these models were different in terms of predicting the experimental data.

Keywords: *Global radiation, Qassim, relative humidity, temperature, atmospheric pressure, Saudi Arabia*

1. Introduction

Solar radiation and its components are the most important and renewable energy source, affecting global climate and energy budget studies; hence the accessibility of solar radiation data is essential for the research community. Global radiation data are essentially required for different applications such as the architectural design of solar energy systems. Information on global solar radiation is not only needed at specific locations but by the worldwide community, Li and Lam (2000); Lu , et al. (1998); Zekai (2008); El-Sebaii et al. (2010)

The measurement of solar radiation requires equipment such as pyranometers, which need regular maintenance and calibration, Chineke (2008). For many developing countries such costly equipment is not usually available; hence elaboration of an alternative method using the available meteorological data to calculate and model the global radiation data is a common practice. Several empirical and semi-empirical models have been parameterized using available meteorological and geographical parameters to calculate solar radiation. These include sunshine hours, air temperature, latitude, and water vapor, El-Sebaii et al., (2010); Alvaro et al. (2013); Maghrabi (2009); Maghrabi et al. (2008); Antonio et al. (2015); Bulent, et al. (2015); Trabea and Shaltout (2000); Li, et al.(2013).

In this work, data on atmospheric pressure, relative humidity (RH) and air temperature have been used to

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model the monthly average daily global radiation for Qassim City, central Saudi Arabia.

2. Experimental Data and Validation Methods

Mean monthly global solar radiation data on a horizontal surface (H) were obtained from the Saudi Arabian Solar Radiation Atlas, published by the Saudi King Abdulaziz City for Science and Technology (KACST). The atlas has two versions. The first contains data collected by the Ministry of Agriculture and Water from 1971 to 1980 compiled by KACST; the second measurements of the global horizontal radiation between 1994 and 1996 obtained from KACST's solar radiation network, KACST (1999). Meteorological information for the two periods was obtained from the Presidency of Meteorology and the Environment (PME). Clear sky data were only considered in this study.The monthly averages of the extraterrestrial global radiation (Ho) were calculated for the given periods using the procedures (Duffie and Beckman 1991) as follows.

$$Ho = (1/\pi) Isc E0 (\cos\lambda \cos\delta \sin ws + (\pi/180) \sin\lambda \sin\delta ws) \qquad \text{(eq. 1)}$$

Isc is the solar constant 1376 Wm^{-2} ,Eo is the correction factor of the Earth's orbi calculated by:

$$E0 = 1.00011 + 0.034221 \cos\alpha + 0.00128 \sin\alpha + 0.000719 \cos(2\alpha) + 0.000077 \sin(2\alpha)$$

(eq. 2)

α is the day angle, obtained from:

$$\alpha = 2\pi(\text{nday} - 1)/365 \qquad \text{(eq. 3)}$$

δ is the solar declination (in degrees),

$$\delta = (180/\pi).(0.006918 - 0.399912\cos\alpha + 0.070257\sin\alpha - 0.006758\cos(2\alpha) + 0.000907 \sin 2\alpha - 0.002697 \cos 3\alpha + 0.00148 \sin(3\alpha)) \qquad \text{(eq. 4)}$$

and the hour angle of the Sun ws (in degrees) is calculated as:

$$ws = \cos{-1} [-\sin\lambda\sin\delta/(\cos\lambda\sin\delta)] \qquad \text{(eq. 5)}$$

We first developed and tested the performance of the several models using regression methods. The calculation procedures began with simple correlation between the clearance index H/Ho (ratio of the measured global radiations to the average daily extraterrestrial radiation) and each meteorological parameter individually; then multiple regression analysis, using two and three parameters, was carried out. The best performing model was validated using an independent set of global radiation measurements for the period between 2003 and 2005. Finally, we selected several models, with different parameters, from the literature and tested their predictability against the measured global radiation.

The calculated H/Ho values were assessed in terms of mean percentage error (MPE), mean bias error (MBE), and root mean square error (RMSE), calculated as:

$$MPE = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{V_{imeas} - V_{ical}}{H_{imeas}} \times 100\right) \quad \text{(eq. 6)}$$

$$MBE = \frac{1}{N}\sum_{i=1}^{N}(V_{imeas} - V_{ical}) \quad \text{(eq. 7)}$$

$$RMSE = \frac{1}{N}\sum_{i=1}^{N}\sqrt{(V_{imeas} - V_{ical})^2}\ , \quad \text{(eq. 8)}$$

where V_{imes} and V_{ical}, are the measured and calculated (H/Ho) values respectively, and N is the number of the measurements The significance of the proposed model was tested using t-statistics calculated according to Stone (1993), as:

$$t - stat = \sqrt{\frac{(n-1)MBE^2}{RMSE^2 - MBE^2}} \quad \text{(eq. 9)}$$

3. Results and Discussions

3.1 Model parameterisation

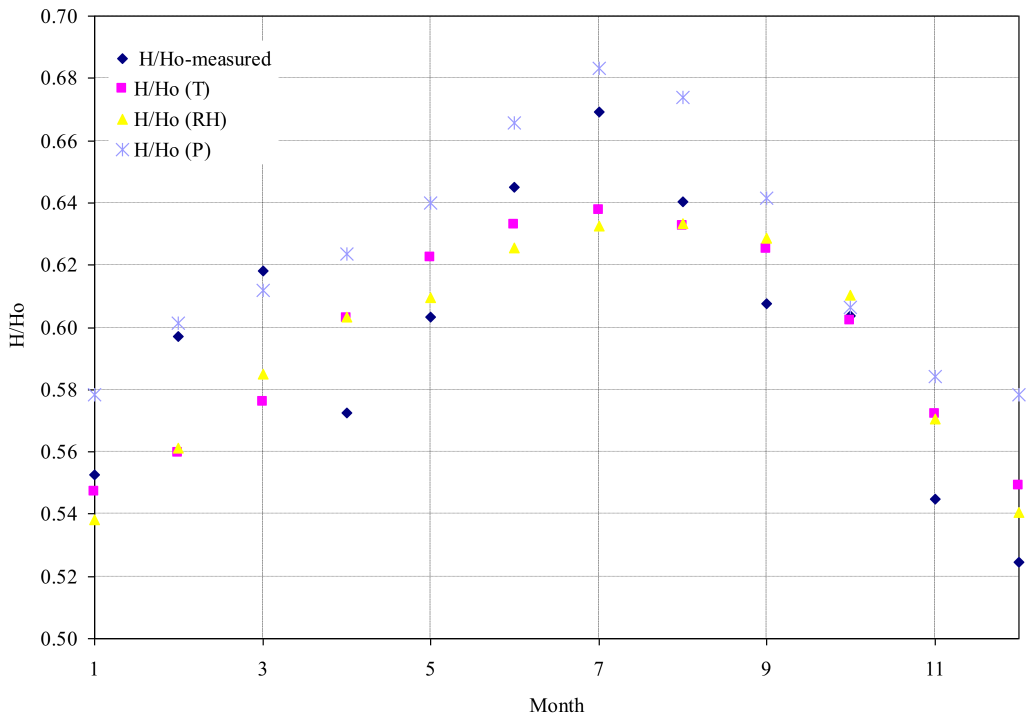
Table (1) presents the regression equations between the measured clear sky index and single, two, and three meteorological parameters. The statistical results of these equations are also given. It can be seen that the statistical parameters vary from one model to another. All the models presented an MPE below 2%, which can be considered an excellent performance. Additionally, all the models were significant according to their t-values, which were smaller than the critical value (3.106).

The three-variable models (eq. 16) presented the lowest RMSE and MBE and the highest correlation coefficient. The correlation coefficient of this equation was 0.98, and the MPE, RMSE and MBE were, respectively, 0.15%, 0.02, and -1.1×10^{-4}. The two-variable models showed improvements in their correlation coefficients; their MBE, RMSE and MPE values were not as good as those of the one-variable models. Models with air pressure (as either single or second variable) gave a poorer performance than those use the air temperatures.

Table 1: Results of the regression analysis of the clearance index, H/Ho (ratio of the measured global radiations to the average daily extra-terrestrial radiation) and meteorological parameters.

Equation	R	MBE	RMSE	MPE	t
$\frac{H}{Ho} = 0.004T + 0.491$ (eq. 10)	0.85	0.0009	0.021	0.3340	0.183
$\frac{H}{Ho} = 0.0023RH + 0.6556$ (eq. 11)	0.86	-0.003	0.023	-0.38	0.455
$\frac{H}{Ho} = -0.0084P + 8.50$ (eq. 12)	0.88	-0.008	0.020	0.0349	0.078
$\frac{H}{Ho} = 0.649 - 0.0021RH + 0.00016T$ (eq. 13)	0.80	-0.002	0.024	-0.261	0.351
$\frac{H}{Ho} = 9.702 - 0.0021Rh + 0.00016T$ (eq.14)	0.91	0.0283	0.032	1.8556	5.93
$\frac{H}{Ho} = 7.463 - 0.0071P - 0.0003RH$(eq. 15)	0.91	0.001	0.018	0.345	0.491
$\frac{H}{Ho}$ =10.750-0.0068T-0.0105P-0.003RH (eq. 16)	0.98	-0.0001	0.0206	0.1555	0.033

Fig.1 shows the monthly variations of the measured and the calculated global solar radiation values obtained from (a) single and (b) two-variable models. It is obvious that the pressure-based model always overestimated the measured values. On the other hand, the RH-based and T-based models slightly overestimated the measured values in the months September, November and December and underestimated the measurements in the remaining months. Two-variable models showed the same behavior as the single T- and H-based models. All the models highly overestimated the global radiation measurements in April and May. This can be explained by the effect of the pre-monsoon dust events which are very frequent during these two months.



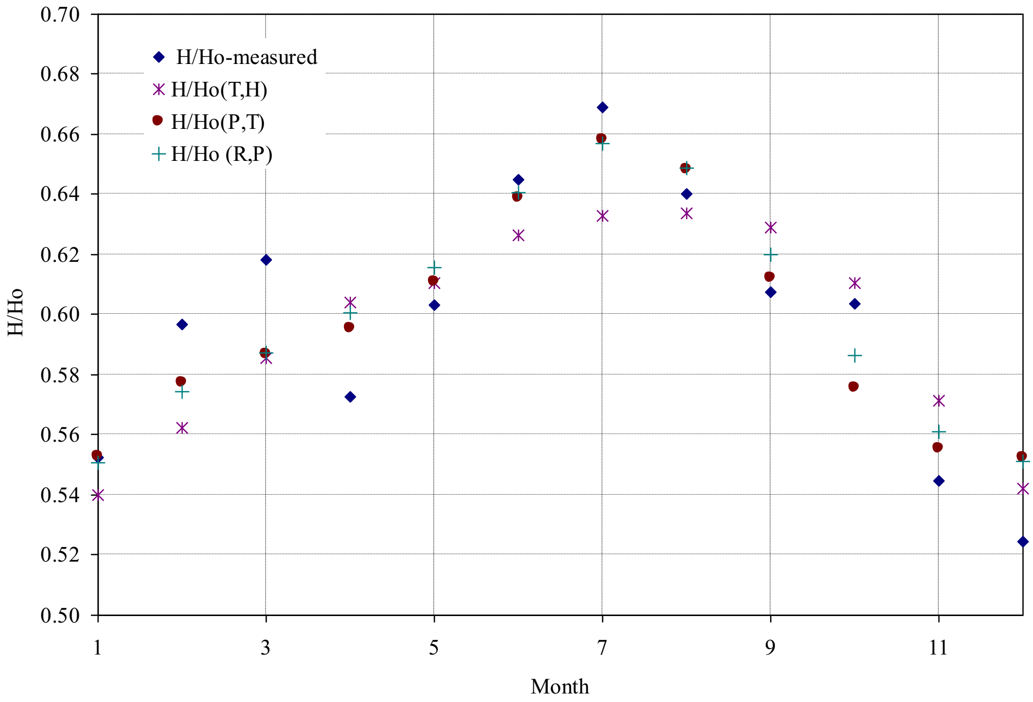


Fig 1. Monthly measured and predicted H/Ho from (a) single and (b) two-variable models.

Fig.2 displays the monthly measured and the calculated radiation from equation (16) (the model contains all three variables). Fig.3 is the scatter plot for the predicted and measured values. It is very evident that the three-variable model showed less deviation from the measured values and predicted with high accuracy. The data closely lie in the vicinity of the 1:1 line. The regression equation for the measured and predicted values has a slope of 0.98 (nearly equal to one) and an intercept of 0.01 (nearly equal to zero). This indicates a distinct relationship between the predicted and measured global radiation and rationalizes the excellent predictability of the model. Student's t-tests for this linear relationship at a significance level of $\alpha = 0.01$ were carried out and showed a t-value of 0.32, which is less than the critical value (3.106). This indicates the significance of the developed model in predicting the measured global solar radiation in Qassim.

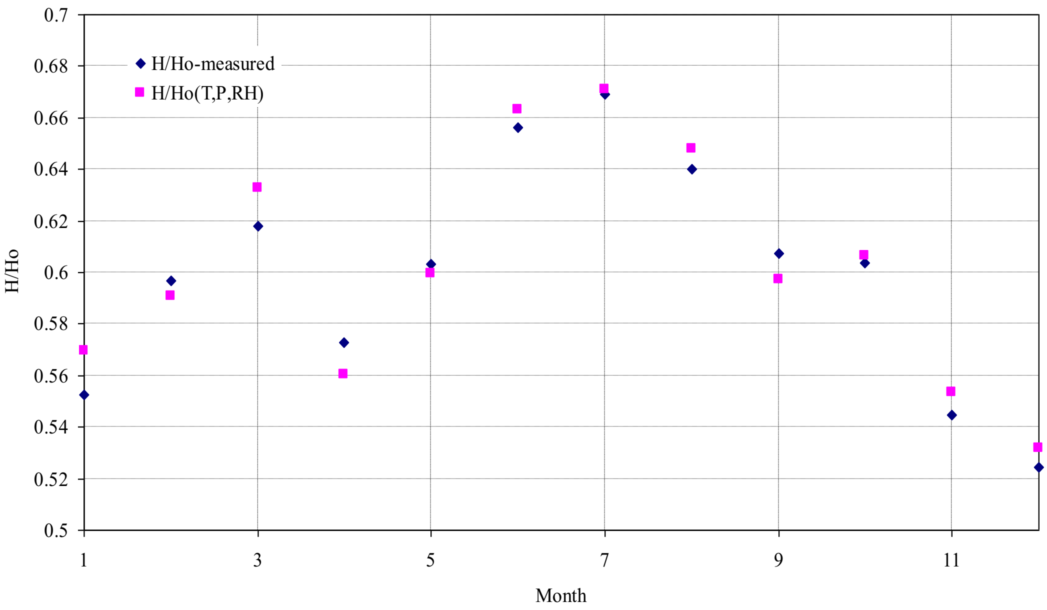


Fig.2. As in Fig.1, the measured data were compared with the predicted values calculated using equation (16).The dashed line is the 1:1 line and the straight line is the regression line.

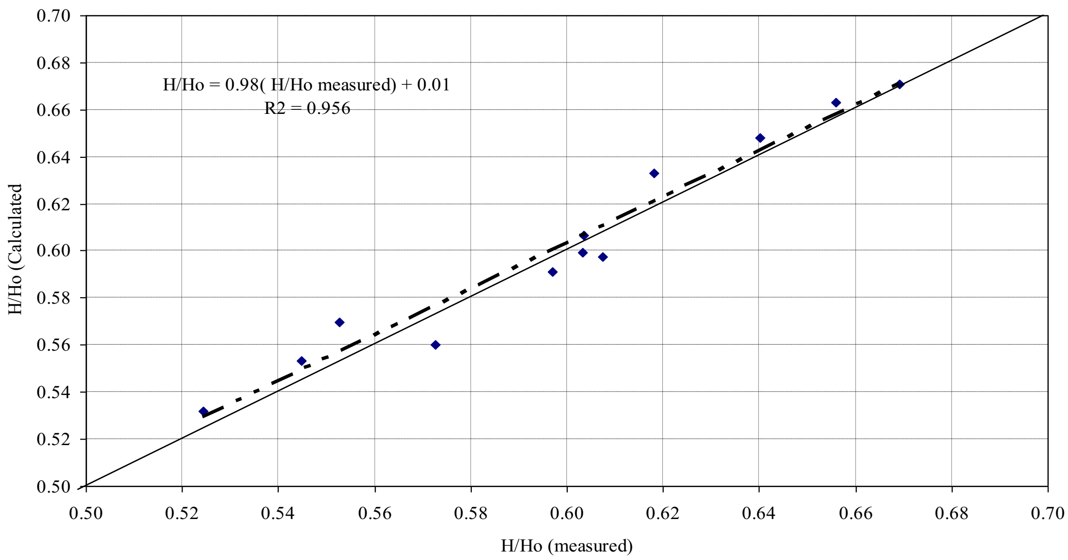


Fig.3. The measured H/Ho plotted against predicted values using equation (16). The straight line is the 1:1 line and te dashed line is the regression line between the two values.

3.2 Model Validation

The prediction of the proposed model (equation 16) for the global radiation in Qassim was tested using an independent data set. These data contain the mean monthly data on global solar radiation and the corresponding meteorological parameters for the period between 2003 and 2005. These data were obtained from the Saudi Presidency of Meteorology and the Environment.

Fig.4 indicates the monthly measured clearance index and the calculated values obtained from the model for the period between 2003 and 2005. The calculated H/Ho gives MPE =2.3 %, MBE -0.003, RMSE = 0.034, and t value =0.0921. These statistical results indicate an adequate performance of the model for this data set.

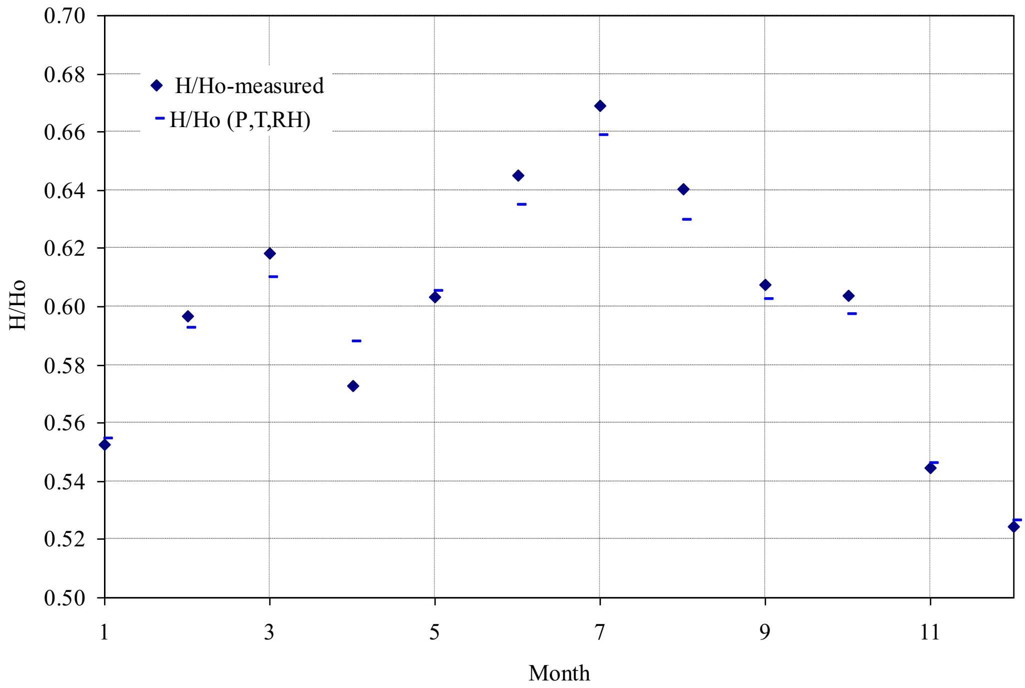


Fig.4. Monthly measured data for the period between 2003 and 2005 compared with their predicted values using the proposed model.

Fig.5 demonstrates the relationship between the measured and the predicted values of the clearance index for these data. The results show a close distribution of the data points around the 1:1 line, which verifies the ability of the model to predict global solar radiation in Qassim using independent measurements. The slope of the regression results for the measured and predicted values was 0.89 and the intercept was 0.052.

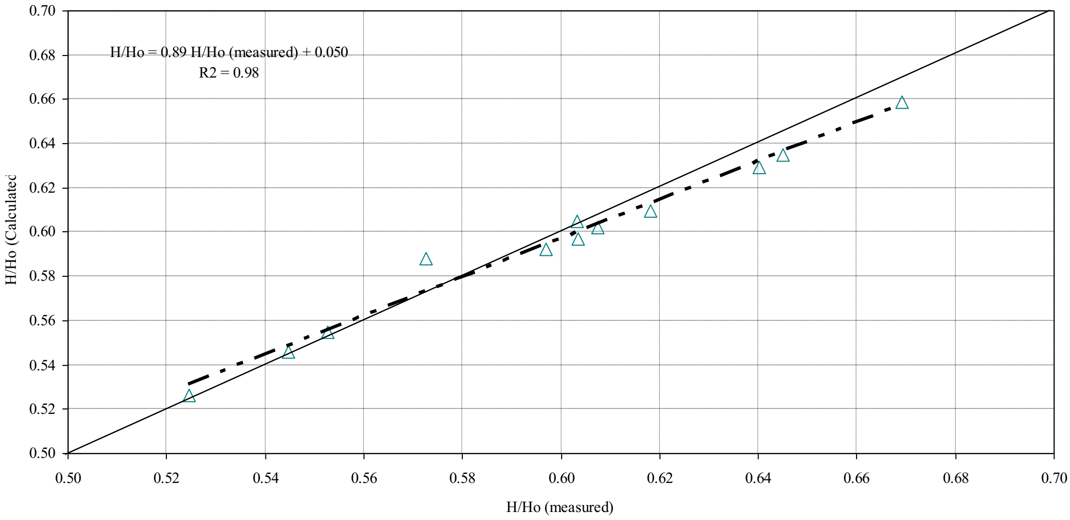


Fig. 5. As in Fig. 3, the figure plots the measured global solar radiation against the calculated values but for data between 2003 and 2005.

3.3 Comparisons with Other Models

Several models for predicting global radiation using meteorological parameters have been developed using data from different places around the world. In this study nine models were selected and their performances in predicting the measured global radiation data for Qassim for the period 1971 to 1996 were tested. Table (2) presents the functional form for the selected models and their statistical indicators. It can be seen that each model performed differently from the others. The RMSE values for all the models ranged between 0.27 and 0.069, MBE between 0.043 and 0.18. Apart from Bristow-Champbell model, all the models showed MPE values of less than 10%. Li et al.(2013) model was the best followed by the Adaramola (2012) model in predicting the measured data in Qassim. These two models contain three variables on them. Contrary, Bristow-Champbell (1984), Hargreaves et al. (1985), and Li et al. (2013) models showed the highest errors in estimating the measured data. According to the statistical tests all the models have poorer prediction in comparison with the proposed model in this study (equation 16) or even the single and multiple models.

Table 2: Functional of some of the selected models from the literature to calculate the measured H/Ho values for Qassim. The statistical results (MBE, RMSE, and MPE) for their predications are given.

	Form	MBE	RMSE	MPE(%)
Li et al (2013)	$\frac{H}{Ho}$ =0.064-1.1130T	0.132	0.231	5.43
Li et al (2013)	$\frac{H}{Ho}$ =1.025-0.879RH	0.143	0.272	8.620
Chen et al. (2004)	$\frac{H}{Ho} = 0.08 + 0.21(T_{max} - T_{\min})$	0.125	0.212	6.751
Adaramola (2012)	$\frac{H}{Ho}$ =1.419-1.1973(Tmin/Tmax)	0.161	0.201	5.820
Hargreaves etal 1985	$\frac{H}{Ho} = 0.153(T_{\max} - T_{\min})^{0.5} - 0.033$	0.146	0.261	9.351
Adaramola (2012)	$\frac{H}{Ho}$ =0.77-0.4656(RH/100) (Tmin/Tmax)	0.102	0.0749	4.793
Adaramola (2012)	$\frac{H}{Ho} = 0.845 - 0.464$(RH/100)	0.071	0.086	5.721
Bristow-Champbell (1984)	$\frac{H}{Ho} = 14.35[1 - \exp(-0.009(Tmx - T\min))^{0.549}$	0.183	0.136	10.457
Li et al (2013)	$\frac{H}{Ho}$ =-1.315+0.138(Tmax-Tmin)+0.8244RH	0.093	0.069	4.940

4. Conclusion

Solar radiation data are of great importance in many applications such as the design of solar energy systems and energy budget studies. In this study, monthly average daily global radiation on horizontal surface measurements between 1971 and 1998 were correlated with three meteorological parameters to develop an empirical model to estimate the global radiation for Qassim city, Saudi Arabia. These parameters are the air pressure, the mean air temperature and the relative humidity. The estimated radiation from the model presented excellent agreement with the measured data. The model has a correlation coefficient of 0.988, RMSE = 0.02, MBE = -1.1×10^{-4} and MPE less than 1 %. The model demonstrated an accurate estimation for the global radiation for Qassim using an independent data set for the period between 2003-2005. The performances of some models from the literature were conducted against the measured data for the period 1971-1998. The performances of these models were different in terms of predicting the experimental data

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