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Global Solar Radiation over Al-Baha City, KSA: Comparison of Predicted Models and Measured Data

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Abstract*— The main objective of this paper is to predict and test the applicability of the empirical models available for computing the monthly average daily global radiation on a horizontal surface, in Al-baha city, KSA. The predicted models were compared on the basis of many statistical error tests such as the relative percentage error (e%), the mean percentage error (MPE), mean bias error (MBE), root mean square error (RMSE). Also, a comparison between the predicted and measured data were performed. From experimental data, it is found that the site receives the maximum values of solar radiation in May while the minimum values of solar radiation in January. Different models (eleven models) classified into three categories were nominated from the literature. After performing regression analysis and evaluating these models, according to the measured data, the best model for estimating the global solar radiation on a horizontal surface will be recommended for predicting the global radiation over Al-Baha city, KSA. The relative percentage error was in the range of 0.48% and 1.8% and never exceeded 5%. The variations between the measured and calculated values of the global solar radiation for the months of the year were performed. A good agreement between the model results and the measured data was obvious.

***Keywords*— Empirical models, Global solar radiation, Saudi Arabia, Sunshine duration.**

I. INTRODUCTION

A global study of the world distribution of global solar radiation requires knowledge of the radiation data in various countries and for the purpose of worldwide marketing, the designers and manufactures of solar equipment will need to know the average of global solar radiation available in different and specific regions [1]. Saudi Arabia experiences more than an average global solar radiation (GSR) value of 2.0 MWh/m^2 yearly on horizontal surface. Figure 1 illustrates the long term mean values of sunshine duration and GSR on horizontal surfaces at 41 locations of the country [2, 3]. A. Hepbasli, and Z. Alsuhaibani [4] were made a key review on present status and future directions of solar energy studies and applications in Saudi Arabia. Behrang et al. [5] used particle swarm optimization technique (PSO) to establish, develop and test only sunshine-based models for predicting monthly average daily global radiation for seventeen Iranian cities for which long-term global solar radiation data were available.

Several empirical models have been developed to calculate global solar radiation using various parameters such as extraterrestrial radiation, sunshine hours, maximum temperature, mean temperature, soil temperature, relative humidity, cloudiness and evaporation, total perceptible water, number of rainy days, altitude and latitude [6-8].

A critical review on the estimation of daily global solar radiation from sunshine duration was performed by Yorukoglu, M. and Celik A. [9]. Models such as the Angstrom–Prescott equation are used to estimate global solar radiation from sunshine duration. In the literature, researchers investigate either the goodness of the model itself or the goodness of the estimation of global solar radiation based on a set of statistical parameters such as coefficient of determination (R^2), root mean square error (RMSE), mean bias error (MBE), mean absolute bias error (MABE), mean percentage error (MPE) and mean absolute percentage errors (MAPE). A case study of the estimation models and global solar radiation estimation from sunshine duration is presented using five different models (linear, quadratic, cubic, logarithmic and exponential), which are the most common models used in the literature, based on 6 years long measured hourly global solar radiation data. A general formula for estimation of the monthly average daily global solar radiation in China was investigated by Jin Z. et al. **[**10**].** They were used the relative duration of sunshine as a single independent variable, the most accurate equation that is expressed in a third order form was obtained for each station. Estimation of monthly-mean daily global solar radiation based on moderate resolution imaging spectroradiometer (MODIS) and tropical rainfall measuring mission satellite (TRMM) products was studied by Jun Qin et al. [11]. They used the artificial neural network (ANN) to build the mathematical relationship between measured monthly-mean daily GSR and several high-level remote sensing products available for the public.

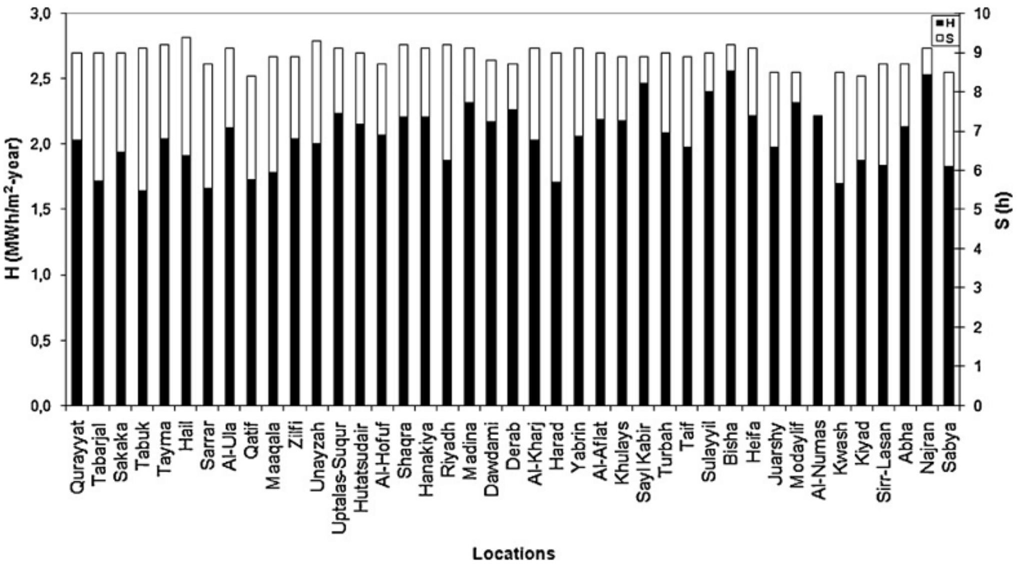

Fig. 1 Long term mean values of sunshine duration (S) and Global Solar Radiation (H) on horizontal surface in various locations of Saudi Arabia.

Instantaneous global solar radiation on horizontal surface has been determined by using simple calculation method and a comparison of measured and calculated values has been made [12]. Therefore, the best approach model in the estimation of global solar radiation has been determined. Moreover, with a view to show performance analysis of models, the statistical testing methods such as MAPE, MABE, and RMSE were used. The results reveal that a new model seems highly acceptable for predicting the solar radiation in Osmaniye. Linear, quadratic and cubic empirical as a general equation for throughout the year are generated to estimate global solar radiation in Eastern Mediterranean Region (EMR) which covers the four main cities (Adana, Mersin, Antakya and Kahramanmaras) by using the meteorological data in the Turkish State Meteorological Services [13]. Regression models were estimated for each month separately and annually by curve estimation techniques with MINITAB statistical program. The monthly linear, quadratic and cubic models for estimating monthly average global solar radiation are validated as well. Finally, a comparison between monthly models and general models is performed by statistical test methods such as R^2, MPE and MAPE. According to statistical test results, the use of cubic general model for EMR is recommended.

From literature survey for all studies inside and outside KSA, there is no information about the global solar radiation in Al-Baha city, KSA. So, the main objective of this study is to predict and test the applicability of all models for computing the monthly average daily global radiation on a horizontal surface, in Al-Baha city, KSA. The different measured and meteorological data will be used to calculate the monthly mean values of global radiation using all predicted models. The predicted models will compared on the basis of many statistical error tests such as the relative percentage error (e%), the mean percentage error (MPE), mean bias error (MBD), root mean

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square error (RMSE). According to the results, the best model for estimating the global solar radiation on a horizontal surface will be recommended for predicting the global radiation over Al-Baha city, KSA.

II. SITE DESCRIPTION

Al-Baha Province as shown in Fig. 3 is situated in the south-western part of Saudi Arabia between the Holy Makkah and Asir Regions, with a population of about 500,000. It is the smallest province in the kingdom of Saudi Arabia (about 10362 km²), situated between longitudes 42° E and latitudes 20° N. This Province is known for its beauty and has many tourist attractions such as forests (about 53 forests), wild life areas, valleys, and mountains. The region is divided by huge and steep Rocky Mountains into two main sectors, a lowland coastal plain at the west, known as “Tihama”, and a mountainous area with an elevation of 1500 to 2450 m above sea level at the east, known as “Al-Sarat or Al-Sarah” which forms a part of Al-Sarawat Mountains.

The climate in Al Baha Province is greatly influenced by its varying topography. It is generally moderate in summer and cold in winter with average temperatures ranging between 12–23 °C. In Tihama, the climate is hot in summer, warm in spring and mild in winter, with humidity ranging between 52% - 67%, and a rainfall less than 100 mm annually. While in the mountainous area, Al-Sarah, The climate is greatly different from that in Tihama although the two sectors are separated by no more than 30 km. The weather is cooler in summer and winter due to its high altitude. Al-Sarah is exposed to the formation of clouds and fog, and this often happens in winter because of air masses coming from the Red Sea, accompanied by thunderstorms climate is mild and pleasant. Also, rainfall is higher with falls in the range of 229–581 mm. The average rainfall throughout the whole province is 100–250 mm annually.

III. MEASURING DEVICES

Weather station

The measuring data are collected on faculty of engineering, Al Baha University site (Raghdan-Al Baha). This site has an altitude of 2285 m above the sea level and longitudes 42° 26' 47"E and latitudes 20° 02' 28" N. The weather station is fixed on the Faculty of Engineering roof at a height of 11 m from the ground (to prevent the effect of obstacles that may affect the airflow). The measuring device is weather station type (Vantage Pro 2) used to measure Temperature, Humidity, Rain Rate, Wind Speed, Wind Direction, Barometer, Solar Radiation and Ultra Violet.

The measuring device is set to record the reading every 10 minutes then extract that reading from device by software of weather station named Weather Link**.** The measuring device have the following specification: operating temperature -40^{o} to +65 ^{o}C, resolution of barometric pressure 0.1mm Hg, accuracy of solar radiation ±5 of full scale, and accuracy of outside relative humidity sensor ±3%.

The data extracted from software using MS Excel to analyze it by separating the data by its type then calculate the average of each data by hour then by day last by month, also for solar calculation need the duration of sun bright shine to get the daily average in Wh/m^2/d.

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Fig. 2: Map of Al-Baha city (the site studied in the current study).

Sunshine duration sensor

Sunshine Duration (CSD) Sensors are widely used in weather networks and holiday resorts to provide the number of sunshine hours per day for tourist information. In health spas and clinics they contribute to the measurements used in treatment and recovery. In agronomy the amount of sunshine received by crops can be used to help forecast yields. In building automation the CSD 3 can be used as an input to the systems for the control of the internal environment, such as the deployment of sun blinds. CSD 3 measures solar radiation through a high quality glass tube. It has no moving parts and uses photo photo-diodes with specially designed diffusers to make an analogue calculation of when it is sunny. The output is switched high or low to indicate sunny or not sunny conditions. The calculated direct irradiance value is also available. Figure 3 shows a picture for the sunshine duration sensor. The specification of the sunshine duration sensor are: Accuracy > 90% (monthly sunshine hours), Response time < 1 ms, and Accuracy > 90% (direct signal for clear sky).

Fig. 3 The sunshine duration sensor.

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V. MODELS AND STATISTICAL TECHNIQUE

The Used models

Since there is more and more concern on energy conservation and environmental protection, interest has been increasingly focused on the use of solar energy in KSA. For the appropriate and accurate design of solar energy conversion and utilization devices, a proper knowledge of the long term behavior of measured global solar radiation is necessary. However, long term data on global solar radiation are missing or not available and must be estimated for most areas in KSA, especially in remote rural and mountainous areas**.** Many models and correlations to estimate global solar radiation have been found in the literature. Some of them were selected and developed to analyze the radiation in Al-Baha, KSA. Eleven models selected from the literature and classified in three different categories as:

Category 1 is the ratio of monthly mean daily global solar radiation on a horizontal surface to monthly mean daily solar extraterrestrial on a horizontal surface is only function of relative sunshine duration; such that:

$$\frac{Y}{Y_o} = f\left(\frac{n}{N}\right) \qquad (1)$$

Five simple models selected from this category are given as:

- ***Model 1[14,15]:***

$$\frac{Y}{Y_o} = a + b\left(\frac{n}{N}\right) \qquad (2)$$

Where:

Y: monthly mean daily global radiation on horizontal surface (KW h/m^2).

Y_o: monthly mean daily extraterrestrial horizontal surface (KW h/m^2).

n: monthly mean daily sunshine hours (h).

N: monthly mean daily maximum possible sunshine hours (h).

And a & b are empirical coefficients.

- ***Model 2 [16]***

$$\frac{Y}{Y_o} = a + b\left(\frac{n}{N}\right) + c\left(\frac{n}{N}\right)^2 \qquad (3)$$

- ***Model 3 [17]***

$$\frac{Y}{Y_o} = a + b\left(\frac{n}{N}\right) + c\left(\frac{n}{N}\right)^2 + d\left(\frac{n}{N}\right)^3 \qquad (4)$$

- ***Model 4 [18]***

$$\frac{Y}{Y_o} = f\left(\frac{n}{N}\right)^b \qquad (5)$$

- ***Model 5 [18]***

$$\frac{Y}{Y_o} = a\exp\left(b\left(\frac{n}{N}\right)\right) \qquad (6)$$

Category (2) is the ratio of monthly mean daily global solar radiation to monthly mean daily solar extraterrestrial on a horizontal surface is not only function of relative sunshine duration but also function of other meteorological parameters; such that:

$$\frac{Y}{Y_o} = f\left(\frac{n}{N}, T_{avg}, R_h\right) \qquad (7)$$

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Where:
T_{avg} : monthly mean ambient temperature (^oC).
R_h : monthly mean relative humidity (%).

Three simple models selected from this category are given as:

- ***Model 6 [19]***

$$\frac{Y}{Y_o} = a + b\left(\frac{n}{N}\right) + cT_{avg} \qquad (8)$$

- **Model 7** ***[19]***

$$\frac{Y}{Y_o} = a + b\left(\frac{n}{N}\right) + c\,R_h \qquad (9)$$

- ***Model 8 [20]***

$$\frac{Y}{Y_o} = a + b\left(\frac{n}{N}\right) + cT_{avg} + d\,R_h \qquad (10)$$

Category (3) is the ratio of monthly mean daily global solar radiation to monthly mean daily solar extraterrestrial on a horizontal surface is independent of relative sunshine duration but is function of monthly mean relative humidity, monthly mean temperature, monthly mean maximum temperature and monthly mean minimum temperature; such that:

$$\frac{Y}{Y_o} = f(T_{max}, T_{min}, T_{avg}, R_h) \qquad (11)$$

From this category, three simple models are selected as following:

- ***Model 9 [21]***

$$\frac{Y}{Y_o} = a(T_{max} - T_{min})^b \qquad (12)$$

- ***Model 10 [22]***

$$\frac{Y}{Y_o} = a\,(T_{max} - T_{min})^{0.5} + b \qquad (13)$$

- ***Model 11 [19]***

$$\frac{Y}{Y_o} = a + b\,T_{avg} + cR_h \qquad (14)$$

The monthly mean daily extraterrestrial solar radiation on a horizontal surface is given by:

$$Y_o = \frac{24 \times 3600}{\pi} G_{sc}\left(1 + 0.033\cos\frac{360n_{day}}{365}\right) \times \left(\cos\emptyset\,\cos\delta\,\sin\omega_s + \frac{\pi\omega_s}{180}\sin\emptyset\,\sin\delta\right) \qquad (15)$$

Where G_{sc} is the solar constant (equal to 1367 W/m^2), n_{day} is the number of days, $\emptyset$ is the latitude of the location (deg.), and δ and ω_s are the monthly mean daily solar declination and sunrise hour angle, respectively, as:

$$\delta = 23.4\sin\left(\frac{n + 284}{365}\right) \qquad (16)$$

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$$\omega_s = cos^{-1}(-tan\emptyset\ tan\delta) \qquad (17)$$

The monthly mean daily maximum possible sunshine duration is calculated by:

$$N = \frac{2}{15} cos^{-1}(-\tan\emptyset\ tan\delta) \qquad (18)$$

Statistical technique

The prime purpose of the present work is assessment of different proposed models in order to find and introduce the best model of each category for Al-Baha city of KSA. For this purpose, and in order to establish the models for this city, the statistical regression technique based on establishing data series has been used to obtain the regression constants for different models. The final goal is to introduce the best model among all for each city. To achieve this goal, three most commonly statistical parameters of mean percentage error (MPE), mean bias error (MBE) in KW h/m^2 and root mean square error (RMSE) in MJ/m^2 have calculated based on evaluating data series. Also the concept of coefficient of determination (R^2) has been used to make sure that the linear relationship between the predicted values by selected models and the measured values exist. The values of MPE, MBE, RMSE and R^2, respectively, are determined as:

$$\mathrm{MPE} = \frac{1}{x}\sum_{i=1}^{x}\left(\frac{Y_{i,c} - Y_{i,m}}{Y_{i,m}}\right) \times 100 \qquad (19)$$

Where $Y_{i,c}$ and $Y_{i,m}$ are the i^{th} calculated and measured values of Y (MJ/m^2).

$$\mathrm{MBE} = \frac{1}{x}\sum_{i=1}^{x}(Y_{i,c} - Y_{i,m}) \qquad (20)$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{x}\sum_{i=1}^{x}(Y_{i,c} + Y_{i,m})^2} \qquad (21)$$

$$R^2 = \frac{\sum_{i=1}^{x}(Y_{i,c} - Y_{c,avg}).(Y_{i,m} - Y_{m,avg})}{\sqrt{[\sum_{i=1}^{x}(Y_{i,c} - Y_{c,avg})^2][\sum_{i=1}^{x}(Y_{i,m} - Y_{m,avg})^2]}} \qquad (22)$$

where $Y_{i,c}$, $Y_{i,m}$, $Y_{c,avg}$ and $Y_{m,avg}$ are the ith calculated, measured, average calculated and average measured values, respectively, and x is the total number of observations.

VI. RESULTS AND DISCUSSION

Experimental data

In this paper, the solar radiation data for Al-Baha city, KSA, over a twelve months during year 2014 were analyzed. The measured values of monthly average daily solar radiation on a horizontal surface for Al-Baha city are shown in Fig. 4. It is seen that the site receives the maximum values of solar radiation in May approximately 6.5 KWh/m^2 while the minimum values of solar radiation in January approximately 3 KWh/m^2.

Figure 5 shows the monthly mean variations of the sunshine duration over El-Baha city during 2014. It is seen that the maximum sunshine duration during May month. Figures 6-8 show variation of monthly mean relative humidity, air temperature and atmospheric pressure during year 2014 respectively.

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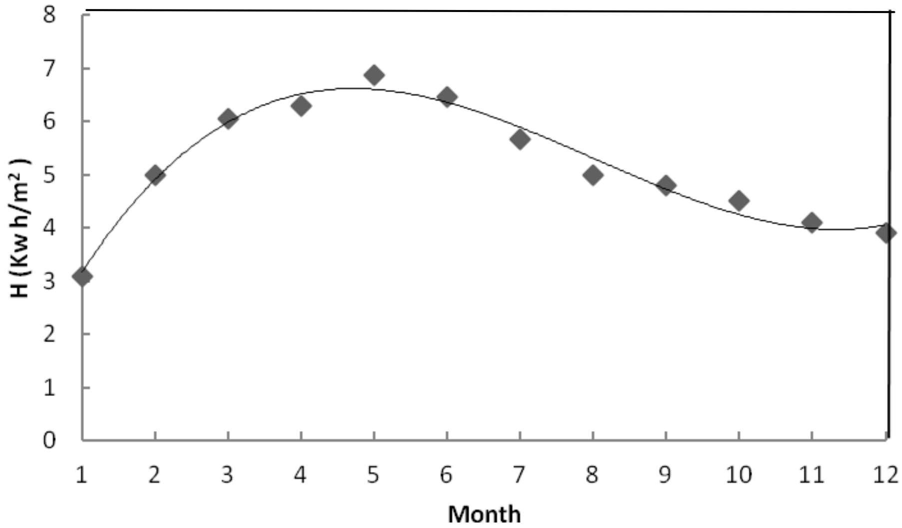

Fig.4 Monthly mean variations of the global solar radiation on horizontal surface (H) in kW h/m^2.

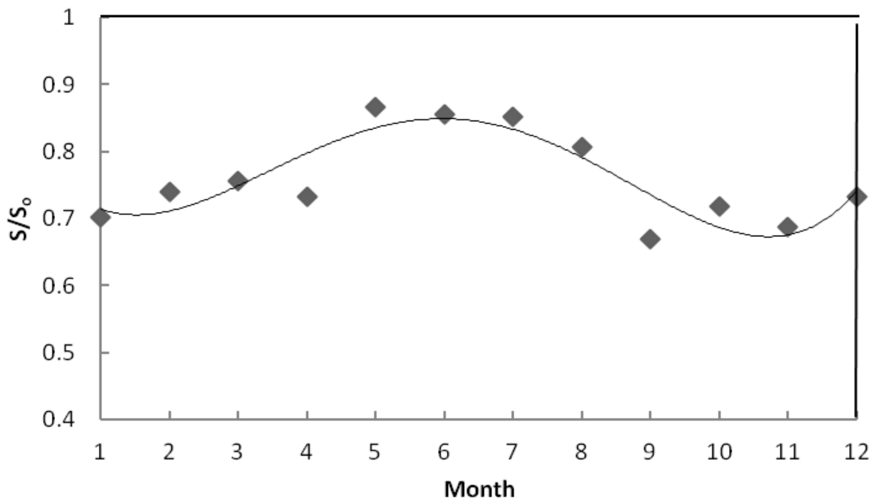

Fig. 5 Monthly mean variations of the sunshine duration.

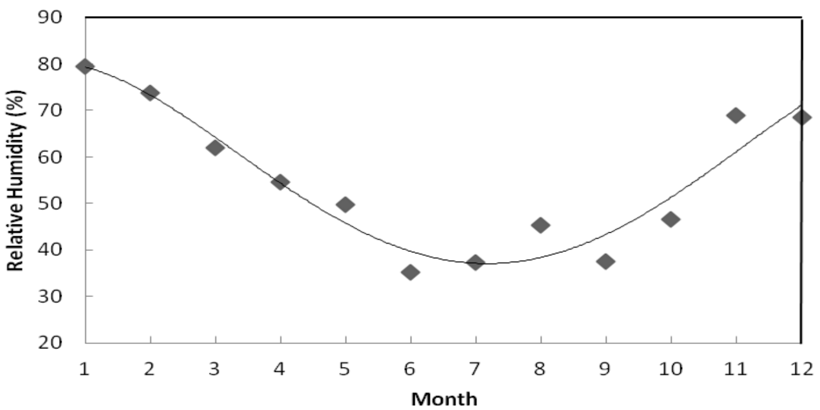

Fig. 6 Monthly mean variations of relative humidity over El-Baha city.

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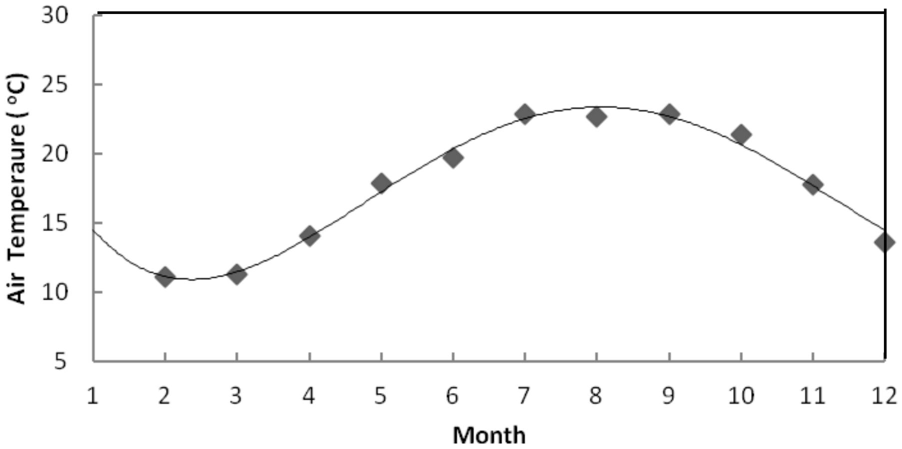

Fig. 7 Monthly mean variations of the air temperature.

Models results

Regression analysis for eleven models in three different categories for the Al-baha city of KSA was conducted using establishing data series. The regression coefficients obtained have been presented in Table 1. Then, for all the models the statistical indicators were calculated using the evaluation data series. The calculated statistical indicators have been presented in Table 2. In order to choose the best model among all of the models, the values of MPE, MBE and RMSE for the best models of different categories were compared.

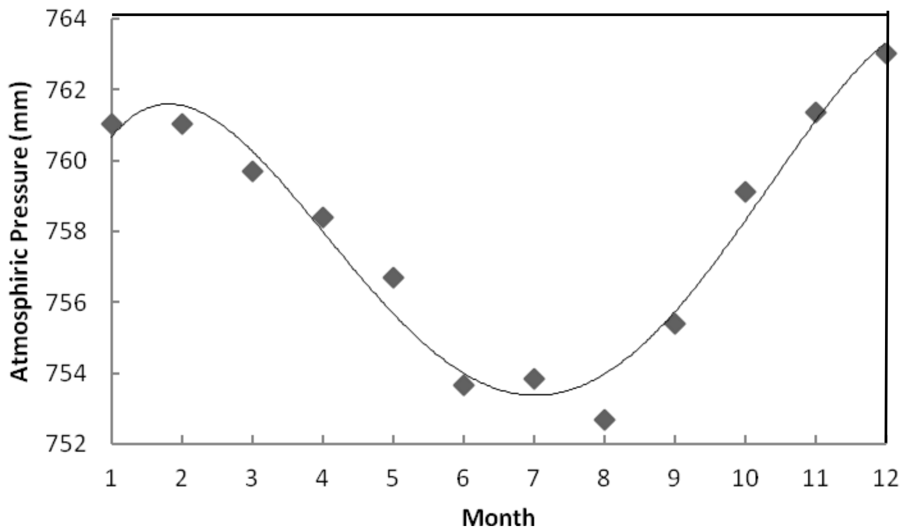

Fig. 8 Monthly mean variations of the atmospheric pressure.

Table 1: Regression coefficients of different models applied for Al-Baha city.

Category	Model	a	B	C
1	1	-0.0003	0.9921	
	2	0.4742	- 0.2417	0.796
	3	10.089	- 38.359	50.96
	4	0.9906	0.9958	
	5	0.2813	1.2921	
2	6	0.007	0.923	0.003

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	7	0.134	0.8213	-0.0006
	8	0.012	0.9564	0.0113
3	9	0.378	0.5	
	10	0.2481	0.2431	
	11	0.426	0.021	0.005

Figure 9 shows MPE, MBE, and RMSE for the best models. It is seen from the figure that, the lowest MPE and MBE values were for model 1 (0.0 9% and 0.000876 kWh/m^2). This means that the best model for predict the global solar radiation over Al-Baha city is model 1. The unsuccessful predictions by the other models of the measured global solar radiation in Al-Baha City do not mean that these formulae are inaccurate. Rather, they mean that these models were proposed in sites having different overall atmospheric conditions, solar inputs, and geographical and astronomical parameters than those found in Al-Baha.
The best model for Al-Baha city is estimated as:

$$H/H_o = - 0.0003 + 0.9921\ (n / N) \qquad (23)$$

Table 2: MPE, MBE and RMSE of different models for Al-Baha city

Category	Model	MPE	MBE (kWh/m^2)	RMSE (kWh/m^2)
1	**1**	**-0.00099**	**0.000876**	**0.047624**
	2	**0.004426**	**0.001135**	**0.045406**
	3	**0.001377**	**0.001073**	**0.035966**
	4	**0.004837**	**0.000877**	**0.047665**
	5	**0.00977**	**0.00136**	**0.045408**
2	**6**	**0.872364**	**0.051555**	**0.092435**
	7	**0.689489**	**0.025044**	**0.094254**
	8	**-0.20183**	**-0.01157**	**0.050871**
3	**9**	**1.492699**	**0.101048**	**0.250971**
	10	**-0.87951**	**-0.04979**	**0.061531**
	11	**5.388272**	**0.285494**	**0.591855**

Figure 10 shows the relative percentage error for the best model (model 1) for each month. The relative percentage error is defined as:

$$e = \frac{Y_{meas} - Y_{cal}}{Y_{meas}} \times 100 \qquad (24)$$

The relative percentage error was in the range of 0.48% and 1.8% and never exceeded 5%. In most cases, the error is far below this value. If the relative percentage error between 10% and +10% is assumed to be within the acceptable range, we can conclude that the model has superior predictions. The highest e values were 1.3% and 1.8% for the months of July and October, respectively. This may be due to the extreme weather conditions found in these two months. Fig. 11 shows the variations between the measured and calculated values of the global solar radiation for the months of the year. It is seen that, a good agreement between the model the measured data.

VII. CONCLUSION

An experimental data for monthly average daily solar radiation on a horizontal surface, sunshine duration, relative humidity, air temperature, and atmospheric pressure over Al-baha city are collected for one year (2014). It is seen that the site receives the maximum values of solar radiation in May approximately 11 KWh/m^2 while the minimum values of solar radiation in January approximately 3 KWh/m^2. The sunshine duration has a maximum values in May month.

Different models (eleven models) classified into three categories were nominated from the literature. After performing regression analysis and evaluating these models, according to the measured data, the best model has been introduced for Al-Baha city. This model is estimated in the form as:

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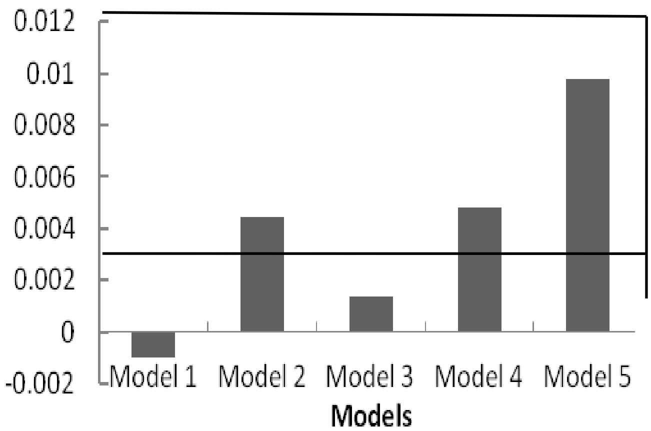
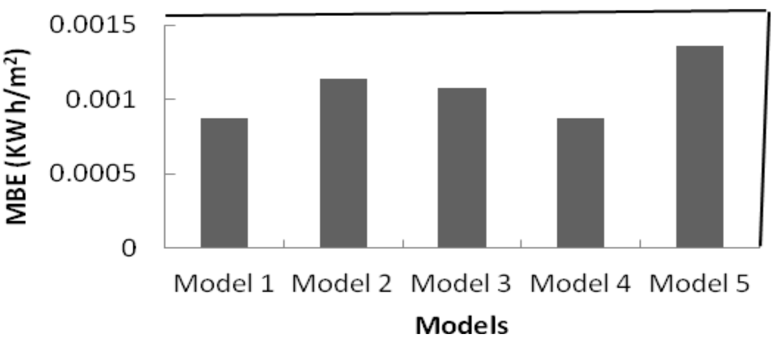
$$H/H_o = - 0.0003 + 0.9921 (n / N)$$

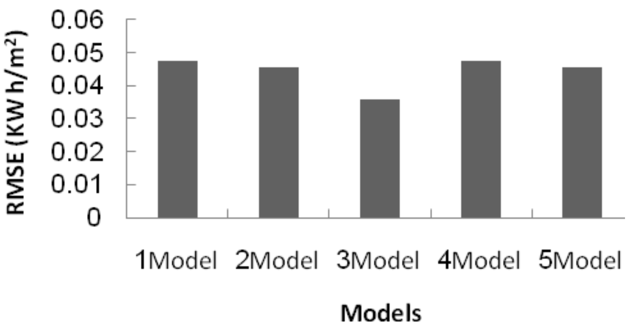
The relative percentage error was in the range of 0.48% and 1.8% and never exceeded 5%. The variations between the measured and calculated values of the global solar radiation for the months of the year were performed. A good agreement between the model results and the measured data was obvious. For more accurate measurement, the data should be take for at least 5 years.



9(a) MPE



9(b) MBE



9(c) RMSE

Fig. 9 MPE, MBE and RMSE of the best models.

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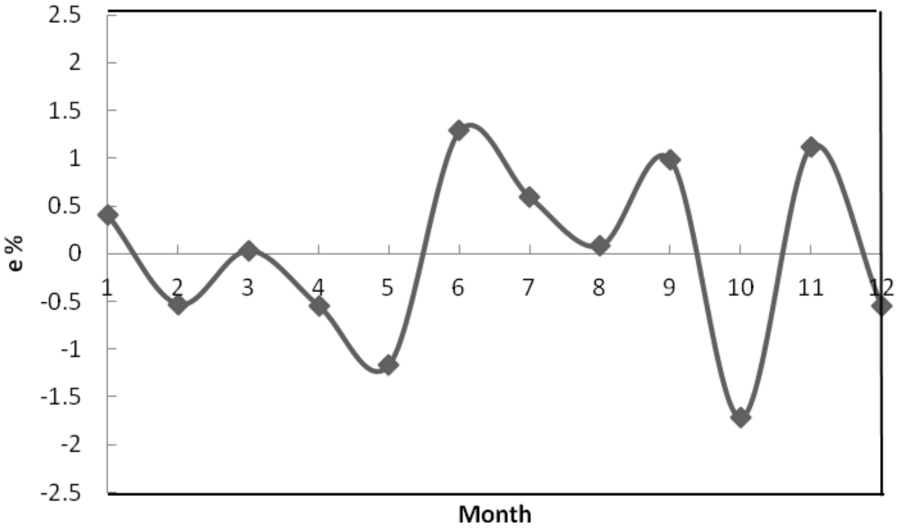

Fig. 10: The monthly relative percentage errors (e, %) for model 1.

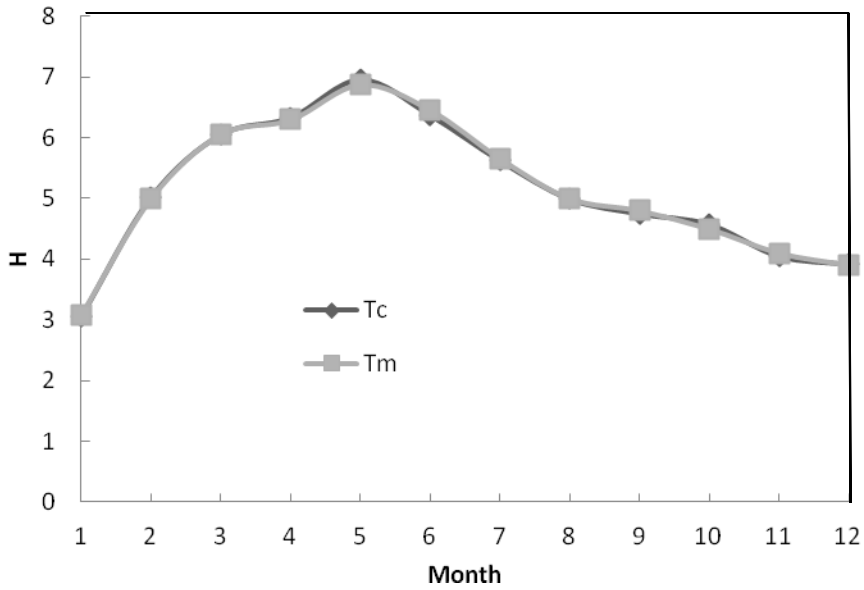

Fig. 11 The monthly measured and calculated values of the global solar radiation (in kW h/m^2) with the model.

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