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ORIGINAL PAPER

A simplified calibrated model for estimating daily global solar radiation in Madinah, Saudi Arabia

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Abstract Solar radiation is the most important parameter in defining the energy budget at the surface thereby influencing the hydroclimate. Several empirical models based on air temperature are developed and used in several decision-making needs such as agriculture and energy sector. However, a calibration against direct observations is a priori for implementing such models. A calibrated model is developed for Saudi Arabia (Madinah) based on observations during 2007–2011. The model $\left(\mathrm{Rs} = \mathrm{A} + B \cdot \mathrm{Rs}_0(\mathrm{T}_{\max} - \mathrm{T}_{\min})^{\mathrm{C}}\right)$ is used to estimate daily solar radiation and results show a correlation coefficient of 0.94. The calibrated model outperforms the uncalibrated model available for this location. To increase the confidence, the calibrated model is also compared with a simple artificial neural network.

1 Introduction

The knowledge of the amount of solar radiation falling on the surface of the earth is of prime importance to engineers and scientists involved in the design of solar energy systems, climate change, hydrology, and agricultural applications. The records of global solar radiation measurements are relatively scarce, due to the cost, maintenance, and calibration requirements of the measuring equipment. In many countries, air temperature is measured at a wide number of locations, and therefore, it is important to study the relation between the solar radiation data and the air temperature data. For example, in Saudi Arabia, the availability of solar radiation data from weather stations is more restricted than air temperature data. Therefore, it is useful to develop methods using the more available data, such as the air temperature data, to estimate the solar radiation.

Empirical models used for estimating solar radiation can be briefly classified as:

- Sunshine-based model is used as an input sunshine duration (Angström 1924; Almorox and Hontoria 2004; Harrouni et al. 2005; Benghanem and Joraid 2007).
- Temperature-based model is widely used since air temperature data are the most measured available meteorological parameter (Allen 1997; Meza and Varas 2000; Mahmood and Hubbar 2002; Bandyopadhyay et al. 2008; Liu et al. 2009a; Tulcan-Paulescu and Paulescu 2008; Wu and Liu 2012).
- Other models using many parameters such as air temperature, humidity, precipitation saturation vapor pressures, and rainfall to estimate solar radiation data have been reported in Yin (1999), Liu and Scott (2001), Thornton and Running (1999), Winslow et al. (2001), and Benghanem and Mellit (2010).

The most investigated parameters are sunshine duration (*S*) and air temperature (*T*). However sunshine data are not always available in most Saudi's locations. Since the air temperature is the most recorded meteorological variable in Saudi Arabia, solar radiation models based on the measured air temperature could be a good solution in this area. Therefore, it is important

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to develop an accurate solar radiation model using geographical location and some commonly available parameters such as maximum (T_{max}) and minimum (T_{min}) air temperature. However, existing empirical models using air temperature are not well adjusted in this location, Madinah, Saudi Arabia.

This paper aims to develop a simple calibrated model for estimating daily global solar radiation. The model accepts the difference between maximum and minimum air temperature ($T_{max}-T_{min}$) and extraterrestrial solar radiation (Rs_0) as input. The main contribution consists of adjusting the possible coefficients (A, B, and C) in order to increase the accuracy of the model $\left(Rs = A + B \cdot Rs_0(T_{max} - T_{min})^C\right)$. The adjusted model has been then compared with some empirical models and a new introduced artificial neural network (ANN) $\left(Rs = \widetilde{f}(Rs_0, T_{max} - T_{min})\right)$.

This paper is organized as follows: Database description and observed correlation are given in Section 2. A brief description of some empirical models is provided in Section 3. Section 4 provides an ANN-based model used for estimating of daily solar radiation. Section 5 deals with the presentation the new calibrated model. Results and discussion are reported in Section 6.

2 Database and observed correlation

The experimental data (global solar radiation, air temperature, relative humidity, etc.) are collected since January 2007 by Solar Energy Laboratory (Physics Department, Faculty of Science, Taibah University). The data have been measured using a meteorological station and collected by using the wireless data acquisition system developed by Benghanem (2010). The used sensors, their sensibility, and the quality of the measured are also reported in Benghanem (2010); the data quality depends on the accuracy of the used sensors. Figure 1a shows the weather monitor software used for collecting the data.

As an example, Fig. 1b, c shows the daily evolution of global solar radiation (Rs) on a horizontal plane and average daily air temperature in Madinah (latitude 24.55° N, longitude 39.70° E). The expression of daily extraterrestrial radiation (Rs_0) is given as:

$$Rs_0 = \frac{24}{\pi} 3,600 \cdot I_{sc} \left[1 + 0.033 \cdot \cos\left(\frac{360 \cdot D}{365}\right)\right] \times \left(\cos\lambda \cdot \cos\delta + \frac{2\pi\omega_s}{360} \sin\lambda \cdot \sin\delta\right). \quad (1)$$

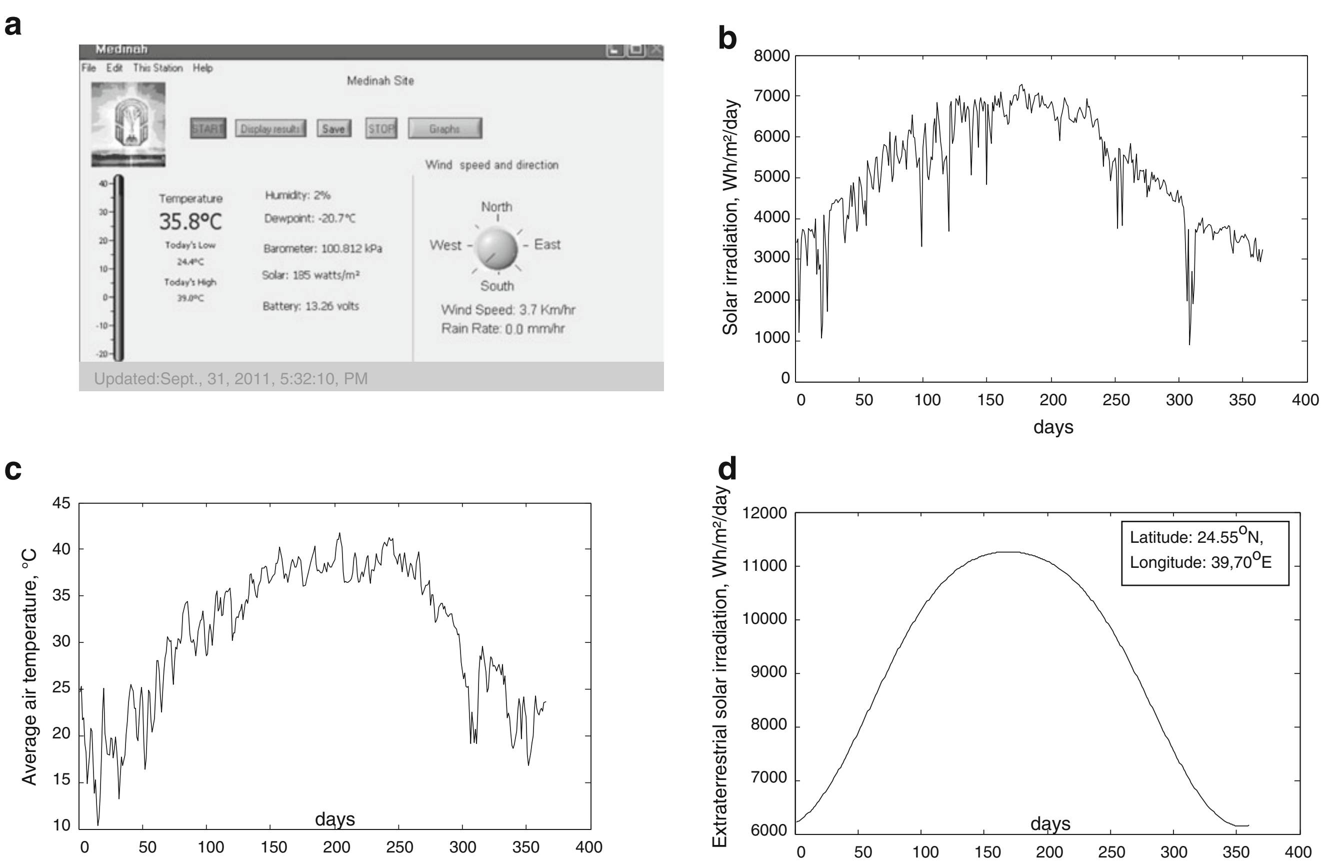

Fig. 1 **a** Weather monitor software. **b** Daily evolution of measured global solar radiation (Madinah, Saudi Arabia). **c** Daily evolution of measured average air temperature (Madinah, Saudi Arabia). **d** Daily evolution of extraterrestrial solar radiation (Madinah, Saudi Arabia)

The only input required to calculate these daily values, for a specific day of the year, is the latitude of the location in degrees.

Where I_{sc} is the solar constant (1,367 W/m^2 day^{-1}), λ is the latitude of the site in degrees, δ is the solar declination in degrees, ω_s is the hour angle of the sun in degrees, and D is the number of days of the year starting from the first of January.

These values can be computed by the following equations:

$$\delta = 23.45.\sin\left(\frac{360(D+284)}{365}\right). \tag{2}$$

The sunrise hour angle ω_s can be calculated if the latitude λ of the site and the solar declination δ are known:

$$\omega_s = \cos^{-1}[-\tan\delta \cdot \tan\lambda]. \tag{3}$$

Figure 1d shows the daily evolution of extraterrestrial solar radiation in Madinah, Saudi Arabia.

The correlation between the daily global solar radiation, air temperature $T_{max}-T_{min}$, and extraterrestrial solar radiation is given in Fig. 2b–d, and the correlation coefficients are 78, 57, and 90 % respectively.

3 Empirical models

Numerous models have been developed using empirical relationships to estimate global solar radiation at ground level from the difference between air temperature extremes. However, the accuracy of these models needs to be verified for each considered location. The investigated empirical models are given below.

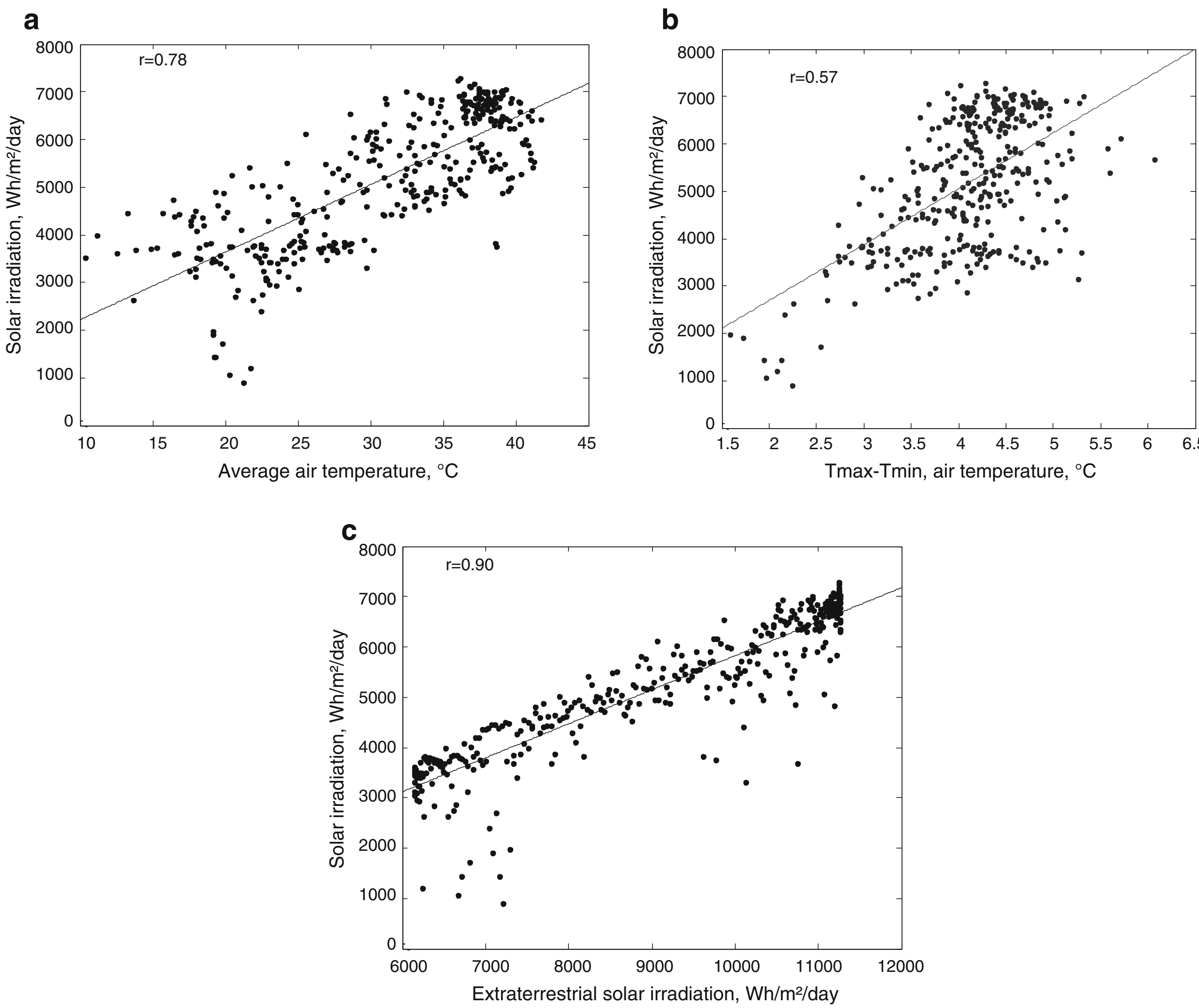

Fig. 2 **a** Correlation between daily global solar radiation and average air temperature (Madinah, Saudi Arabia) r=0.57. **b** Correlation between daily global solar radiation and the difference air temperature ($T_{max}-T_{min}$) in Madinah, Saudi Arabia. **c** Correlation between daily global solar radiation and extraterrestrial solar irradiation (Madinah, Saudi Arabia)

3.1 Model 1

Hargreaves and Samani (1982) suggest that the daily global solar radiation could be estimated from the difference between the mean value of the daily maximum temperatures $T_{\max}$ and the mean value of the daily minimum temperatures $T_{\min}$, by means of the following equation:

$$\mathrm{Rs} = \mathrm{Rs}_0 \cdot \mathrm{K} \cdot (T_{\max} - T_{\min})^{0.5}. \tag{4}$$

The empirical parameter K was set to 0.17 for arid and semiarid regions. Later, Hargreaves (1994) recommended the use of K=0.16 for interior regions and K=0.19 for coastal regions. This coefficient should be derived at a site where data measurements are available. The equation assumes that the difference in maximum and minimum temperature is directly related to the fraction of extraterrestrial radiation received at the ground level. However, there are other factors than solar radiation that can influence the temperature difference. These factors include cloudiness, humidity, latitude, elevation, topography, or proximity to a large body of water.

3.2 Model 2

The new model developed by Hargreaves et al. (1985) is given as:

$$\mathrm{Rs} = \mathrm{Rs}_0 \cdot \left[\mathrm{a}\sqrt{T_{\max} - T_{\min}} + b\right] \tag{5}$$

where a and b are empirical coefficients.

3.3 Model 3

Chen et al. (2004) include a logarithmic variation of air temperature as:

$$\mathrm{Rs}_G = \mathrm{Rs}_0 \cdot [\mathrm{a} \cdot \ln(T_{\max} - T_{\min}) + b] \tag{6}$$

where a and b are empirical coefficients.

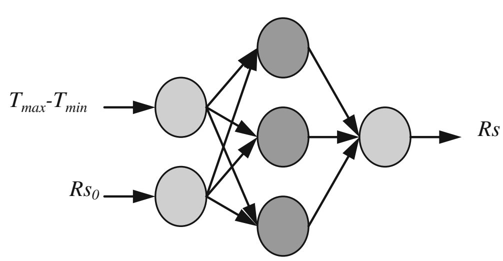

Fig. 3 The simplified obtained MLP architecture

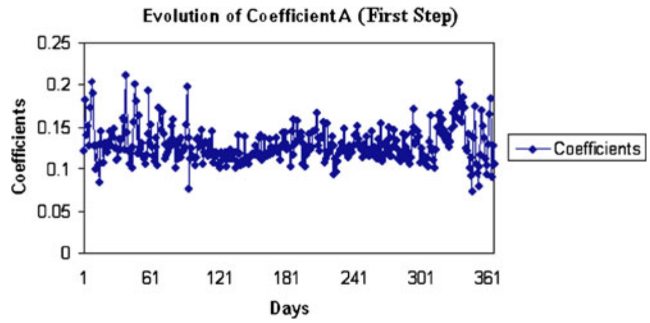

Fig. 4 Evolution of coefficient A (Eq. 18)

3.4 Model 4

The modified Hargreaves and Samani (1982) model developed by Annandale et al. (2002) is given as:

$$\mathrm{Rs} = \mathrm{Rs}_0 \cdot \left[A_\mathrm{n}\left(1 + 2 \times 7^{10^{-5}} \cdot z\right)(T_{\max} - T_{\min})^{0.5}\right] \tag{7}$$

where z is the altitude and A_n is an empirical coefficient. The coefficient must be derived at a site where data measurements are available.

3.5 Model 5

Bristow and Campbell (1984) model proposed a different relation between daily values of the same variables Rs and ($T_{\max}-T_{\min}$), introducing a model with an exponential term:

$$\mathrm{Rs} = \mathrm{Rs}_0 \cdot A \cdot \left[1 - \exp\left(-\mathrm{B}(T_{\max} - T_{\min})^C\right)\right] \tag{8}$$

where A, B, and C are empirical coefficients.

In Eq.8, $T_{\min}$ should be calculated for a generic day as the average of measured values in consecutive days as:

$$T_{\min} = \frac{T_{\min}(j) + T_{\min}(j+1)}{2}. \tag{9}$$

where j is the current day and j+1 is the next day.

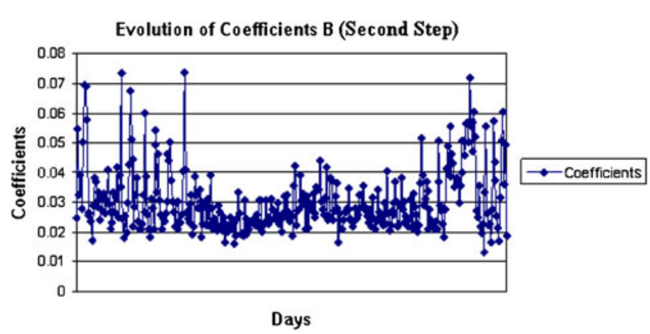

Fig. 5 Evolution of coefficient B (Eq.19)

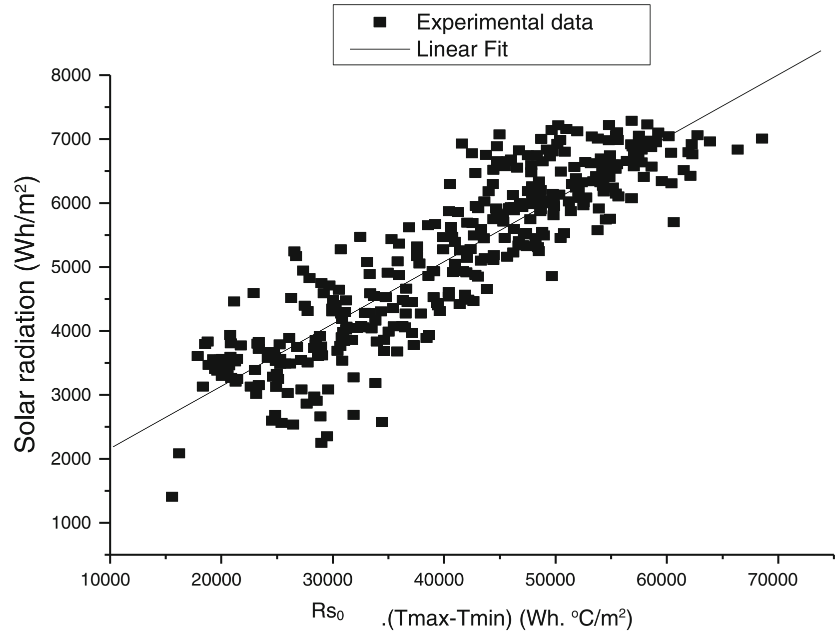

Fig. 6 Observed data: the daily global solar radiation versus extraterrestrial solar radiation and difference of temperature $T_{max}-T_{min}$

3.6 Model 6

Donatelli and Campbell (1998) model estimates the global solar radiation Rs by estimating the extraterrestrial radiation Rs_0 and multiplying by the transmissivity coefficient of the atmosphere:

$$Rs = Rs_0 \cdot A_{DC} \cdot \left[1 - \exp\left(-B_{DC} f\left(T_{avg}\right)\left(T_{max} - T_{min}\right)^2 f\left(T_{min}\right)\right)\right] \quad (10)$$

$$T_{avg} = \frac{T_{min} + T_{max}}{2} \quad (11)$$

$$f\left(T_{avg}\right) = 0.017 \cdot \exp\left[\exp\left(-0.053 T_{avg}\right)\right] \quad (12)$$

$$f(T_{min}) = \exp\left[\frac{T_{min}}{C_{DC}}\right] \quad (13)$$

where A_{DC} stands for the clear sky transitivity, B_{DC} and C_{DC} are empirical coefficients, and $f(T_{avg})$ and $f(T_{min})$ are functions based on mean and minimum temperature.

4 ANN-based model

The well-known multilayer perceptron (MLP) (Mellit 2009; Mellit et al. 2013) is used to build an ANN-based model for estimating the daily global solar radiation. The employed MLP has three layers: an input layer, a single hidden layer, and an output layer. The input layer has two inputs, Rs_0 and $T_{max}-T_{min}$, and its output layer has a single output node: Rs. Thus, the investigated relationship can be given as:

$$Rs = \widetilde{f}(Rs_0, T_{max} - T_{min}) \quad (14)$$

where $\widetilde{f}$ is an approximate function.

A set of 365×3 (three years, 2007–2009) has been used in training the network while a set of 365 (year, 2010) is used for testing the network. The performance function used for training the network is the mean-squared error. Preprocessing steps on dataset were carried out by using the following expression:

$$y = y_{min} + (x - x_{min})(x_{max} - x_{min})^{-1}(y_{max} - y_{min}) \quad (15)$$

where $x \in [x_{min}\ x_{max}]$ and $x \in [y_{min}\ y_{max}]$, x is the original data value, and y is the corresponding normalized variable. y_{min}

Table 1 Regression coefficients *A* and *B*, power coefficient *C*, and correlation coefficient *r*

Power coefficient	Regression coefficients		Correlation coefficient
C	*A*	*B*	*r*
2	2,557.06	0.0138	0.800
1	1,187.96	0.0974	0.894
1/2	159.91	0.2617	0.926
1/3	−203.36	0.3611	0.936
1/4	**−376.01**	**0.4220**	**0.940**
1/5	−473.75	0.4630	0.936
1/6	−535.64	0.4928	0.935
1/8	−608.51	0.5310	0.933

Bold shows the best model

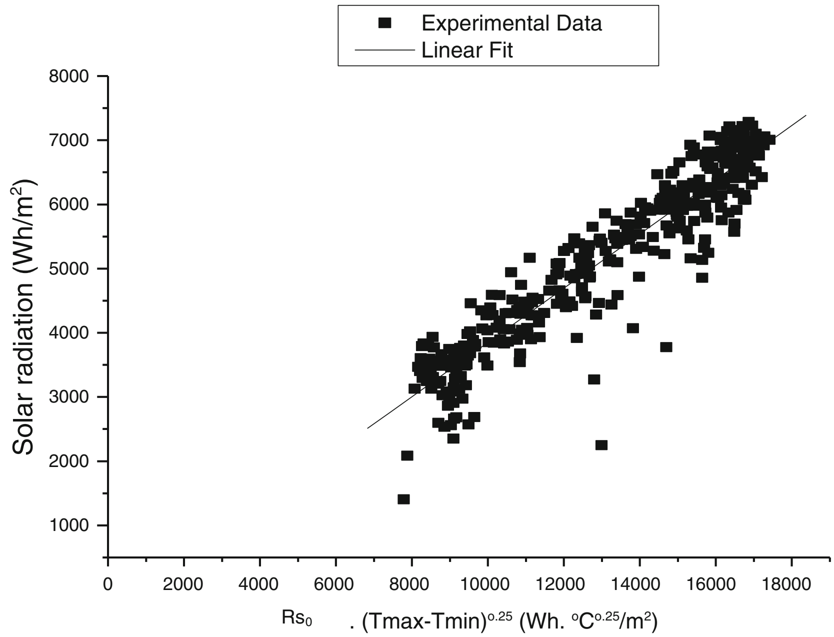

Fig. 7 Experimental data and linear fitting for the new calibrated model

and y_{max} have been assumed to be −1 and 1, respectively. This preprocessing step on the data (input/output) allows the network to perform more efficiently. Different architectures have been evaluated by trial and error, and the simplified one has 3 units within the hidden layer (see Fig. 3).

The simplified ANN-based model is given as:

$$\mathrm{Rs} = (4.6\alpha_1 + 0.05\alpha_2 + 1.15\alpha_3 + 3.65)10^3 \tag{16}$$

Where

$$\alpha_1(\mathrm{Rs}_0, T_{\max} - T_{\min}) = \mathrm{Tansig}(\mathrm{Rs}_0, T_{\max} - T_{\min}) = 2/(1 + \exp(-2(-\mathrm{Rs}_0 - (T_{\max} - T_{\min}) + 1.6))) - 1$$
$$\alpha_2(\mathrm{Rs}_0, T_{\max} - T_{\min}) = \mathrm{Tansig}(\mathrm{Rs}_0, T_{\max} - T_{\min}) = 2/(1 + \exp(-2(2,131\mathrm{Rs}_0 - (T_{\max} - T_{\min}) - 338))) - 1$$
$$\alpha_3(\mathrm{Rs}_0, T_{\max} - T_{\min}) = \mathrm{Tansig}(\mathrm{Rs}_0, T_{\max} - T_{\min}) = 2/(1 + \exp(2(+423\mathrm{Rs}_0 + (T_{\max} - T_{\min}) + 45))) - 1$$

Tansig is a hyperbolic tangent sigmoid transfer function which is given as: $\mathrm{Tansig}(x) = 2/(1 + \exp(-2x)) - 1$.

5 New calibrated model

This section provides the different steps for a new calibrated model. From the above models, we can write the following relationship:

$$\mathrm{Rs} = \mathrm{Rs}_0 \cdot \mathrm{K} \cdot f(T_{\max} - T_{\min}) \tag{17}$$

where K is a regression coefficient.

The first step aims to analyze the following equation:

$$\mathrm{Rs} = \mathrm{Rs}_0 \cdot \mathrm{A} \cdot (T_{\max} - T_{\min}). \tag{18}$$

We found that for winter months, the average value of the coefficient A is 0.132, whereas for summer months, the value is 0.125. Thus, the average value of empirical coefficient A for Madinah site is 0.13. The correlation coefficient (r) between the measured and estimated daily global solar radiation is equal to 89 %. Figure 4 shows the daily evolution of the coefficient A.

In the second step, we have analyzed the following equation:

$$\mathrm{Rs} = \mathrm{B} \cdot \mathrm{Rs}_0 (T_{\max} - T_{\min})^2. \tag{19}$$

It has been found that for winter months, the average value of the coefficient B is 0.0323, and for summer months, the value is 0.0267. The average value of empirical coefficient B is 0.03. The correlation coefficient is equal to 80 %. Figure 5 shows the evolution of the coefficient B during 1 year at Madinah site. However, for another site, this coefficient must be calculated at a site where data measurements are available.

A simple dimensional analysis outlook shows that Eqs. 18 and 19 would not have physical meaning because a function $f(.)$ with unique physical variable, such as $f(T_{\max} - T_{\min})$, cannot be dimensionless. Therefore, the empirical coefficients should be considered as physical variables with units. By analyzing various forms with temperature variable

Table 2 Statistical test between observed and estimated daily global solar radiation for different value of the power coefficient *C*

Model Eq. 20	Correlation coefficient (*r*)	RMSE (Wh/m²/day)	MBE (Wh/m²/day)	MAE (Wh/m²/day)	MPE (%)
$Rs = A + B \cdot Rs_0(T_{max} - T_{min})^2$	0.800	0.210	−0.145	5.17	1.89
$Rs = A + B \cdot Rs_0(T_{max} - T_{min})^1$	0.894	0.178	−0.125	4.98	1.60
$Rs = A + B \cdot Rs_0(T_{max} - T_{min})^{1/2}$	0.926	0.135	−0.086	4.77	1.21
$Rs = A + B \cdot Rs_0(T_{max} - T_{min})^{1/3}$	0.936	0.082	−0.023	4.15	0.74
$Rs = A + B \cdot Rs_0(T_{max} - T_{min})^{1/4}$	**0.940**	**0.063**	**−0.012**	**3.87**	**0.56**
$Rs = A + B \cdot Rs_0(T_{max} - T_{min})^{1/5}$	0.936	0.076	−0.018	4.05	0.68
$Rs = A + B \cdot Rs_0(T_{max} - T_{min})^{1/6}$	0.935	0.120	−0.134	4.34	1.08
$Rs = A + B \cdot Rs_0(T_{max} - T_{min})^{1/8}$	0.933	0.192	−0.157	4.56	1.73

Bold shows the best model

and based on the observed data reported in Fig. 6, we suggest the following equation:

$$Rs = A + B \cdot Rs_0(T_{max} - T_{min})^C \tag{20}$$

where A and B are the empirical coefficients deduced from linear regression analysis and C is a power coefficient which should be derived at the considered site. It is clearly shown that the new equation depends on the extraterrestrial solar radiation (Rs_0) and the difference in maximum and minimum air temperature ($T_{max}-T_{min}$). A description of the mathematical expression of the estimation correlation can be deduced from observed data. In fact, by an iterative process, we have varied the power coefficient C, and by fitting data, we calculate the correlation coefficient between the measured and estimated daily global solar radiation.

Table 1 reports the different regression coefficients A and B, the power coefficient C, and the correlation coefficient (r). With reference to Table 1, it can be seen that, when the power coefficient C decrease, the correlation coefficient increases until the value of C=0.25. After that, the correlation coefficient decreases. Consequently, the adjusted model can be given as:

$$Rs = A + B \cdot Rs_0(T_{max} - T_{min})^{0.25}. \tag{21}$$

The model performance was evaluated in terms of the following statistical error tests: correlation coefficient (r) where a model is more efficient when r is closer to 1, and it indicates also that measured and estimated data are very well correlated; root mean square error (RMSE) where a lower value indicates better estimation; mean bias error (MBE) indicates overall under- or overestimation. Therefore, a good estimation means that the value of MBE would be zero. A positive value of MBE indicates the tendency of the estimation model to underestimate the measured solar radiations, whereas a negative MBE indicates a tendency to overestimate the measured solar radiations; the mean absolute error (MAE) is a quantity used to measure how close estimates are to the eventual outcomes; and the mean percentage error (MPE) is the computed average of percentage errors by which estimated forecasts differ from actual values of the quantity being estimated. The employed errors are given in the Appendix (r, RMSE, MBE MAE, and MPE).

6 Results and discussion

Regression analysis of the experimental data and the derivation coefficients of the model involved with simple and multiple linear regressions have been developed by using Origin software and Matlab. Figure 7 shows the observed

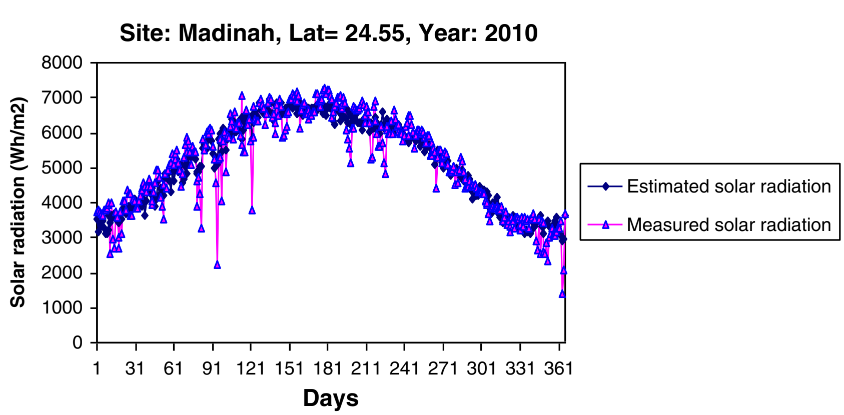

Fig. 8 Estimated and measured daily global solar radiation data (Madinah, 2010)

Table 3 Empirical models coefficients A, B, and C

Models	Authors	Regression coefficients		
		A	B	C
Model 1	Hargreaves and Samani (1982)	0.269	–	–
Model 2	Hargreaves et al. (1985)	0.110	0.336	–
Model 3	Chen et al. (2004)	0.111	0.405	–
Model 4	Annandale et al. (2002)	0.265	–	–
Model 5	Bristow and Campbell (1984)	0.604	1.382	0.502
Model 6	Donatelli and Campbell (1998)	0.577	0.356	0.678

data versus the linear fitting of the calibrated model; as can be seen, good agreement is obtained.

To assess the effectiveness of the calibrated model, the above-mentioned goodness tests have been used. Table 2 reports the statistical test between observed and estimated daily global solar radiation for different value of the power coefficient C. With reference to this table, it has been found that the best correlation coefficient is 94 % for the calibrated model, which is validated by comparing estimated and measured daily global solar radiation (year 2010). The obtained value of MBE for the calibrated (Eq. 21) is −0.012. It means that the underestimation of daily global solar radiation is observed with lower value. The RMSE has been found the lowest for the proposed model 0.063. It means that good estimation of global solar radiation by using extraterrestrial radiation and the difference between maximum and minimum air temperature. The MAE is 3.87 Wh/m^2/day and the MPE is less than 0.6 %. These errors indicate clearly the good accuracy of the model.

It can be concluded that the estimation of global solar radiation can be performed with acceptable accuracy using all tested models. RMSE and r are the primary parameters used to assess the accuracy of the estimation of global solar radiation. The calibrated model makes better options to estimate the global solar radiation in Madinah location from air temperature data.

Estimated versus measured daily global solar irradiation for the Madinah site (year 2010) is shown in Fig. 8. As can be seen that the estimated solar radiation values by the model are very close the measured ones, with relatively high accuracy.

In order to confirm the effectiveness of the calibrated model, six empirical models (Eqs. 4–8 and 10) have been used. Table 3 summarizes the six used models and the calculated coefficients for each model.

A comparison between the six models, the introduced ANN model, and the new calibrated model is reported in Table 4. We have calculated the goodness indicators: r, RMSE, MBE, MAE, and MPE. With reference to these indicators, it can be concluded that the calibrated model performs better than other investigated models: since r=94 %, it is close to 1, MAE=3.87 (Wh/m^2/day), MPE=0.56 %, and RMSE=0.063 (Wh/m^2/day) have lower values, and the MBE=−0.012 which is close to 0. The ANN-based model provides also a good result with a correlation coefficient of 93.7 %.

7 Conclusion and perspectives

In this paper, a new simplified model was calibrated and evaluated for estimating the daily global solar radiation by using measured air temperature data. The calibrated model is basically based on the well-known Hargreaves et al. (1985) model.

It has been demonstrated that the new calibrated model is more accurate than other existing empirical models used in this work. In addition, ANN-based model has proven its accuracy compared to other empirical models. It has been

Table 4 Performance evaluations of six empirical models, ANN-based model, and the new calibrated model (RMSE, MBE, r, MAE, and MPE)

Models	RMSE (Wh/m^2/day)	MBE (Wh/m^2/day)	Correlation coefficient (r)	MAE (Wh/m^2/day)	MPE (%)
Model 1	0.126	0.011	0.907	5.87	1.13
Model 2	0.102	−0.025	0.930	4.65	0.92
Model 3	0.101	−0.062	0.930	4.55	0.91
Model 4	0.125	0.010	0.907	5.95	1.12
Model 5	0.104	0.151	0.928	4.98	0.94
Model 6	0.106	−0.013	0.923	4.76	0.95
ANN-based model	0.100	−0.158	0.937	4.12	0.64
Calibrated model	0.063	−0.012	0.940	3.87	0.56

verified that empirical model-based temperature provides good results if their parameters are correctly adjusted. In fact, the empirical coefficients A, B, and C should be estimated at the considered site.

Our future work will focus on the calibration of the model for other regions in Saudi Arabia as well as to test its effectiveness in the future years.

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Appendix

$$r = \frac{\sum_{i=1}^{n}\left(\mathrm{Rs_e}(i)-\overline{\mathrm{R}}\mathrm{s_e}(i)\right)\left(\mathrm{Rs_m}(i)-\overline{\mathrm{R}}\mathrm{s_m}(i)\right)}{\sqrt{\sum_{i=1}^{n}\left(\mathrm{Rs_e}(i)-\mathrm{Rs_e}(i)\right)}\sqrt{\sum_{i=1}^{n}\left(\mathrm{Rs_m}(i)-\overline{\mathrm{R}}\mathrm{s_m}(i)\right)}}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(\mathrm{Rs_e}(i)-\mathrm{Rs_m}(i)\right)^2}{n}}$$

$$\mathrm{MBE} = \frac{\sum_{i=1}^{n}\left(\mathrm{Rs_e}(i)-\mathrm{Rs_m}(i)\right)}{n}$$

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}\left|\left(\mathrm{Rs_e}(i)-\mathrm{Rs_m}(i)\right)\right|$$

$$\mathrm{MPE} = \frac{1}{n}\sum_{i=1}^{n}\frac{\mathrm{Rs_e}(i)-\mathrm{Rs_m}(i)}{\mathrm{Rs_m}(i)}$$

where n is the number of data, $\mathrm{Rs_m}(i)$ is the ith measured, and $\mathrm{Rs_e}(i)$ is the ith estimated solar irradiance values.

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