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Research Article

Estimation of Daily Average Global Solar Radiation with Nonlinear Regression Models Developed Using Some Meteorological and Geographical Parameters

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ABSTRACT

In this study, it is aimed to develop empirical models that can be used in estimation of daily average solar radiation (RS) based on some meteorological and geographical parameters. Seven estimation models were developed by nonlinear regression analysis method using various combinations of air temperature (T), relative humidity (RH), extraterrestrial radiation (R_a), saturated (e_s) and actual vapour pressure (e_a) parameters. The models were created using the long-term average daily meteorological data of Kahramanmaraş province (1938 – 2020). The models were tested both these long-term average data and daily meteorological data measured at Kahramanmaraş Sütçü İmam University (KSU) in 2019 and 2020. Long-term average daily actual RS data varied between 4.99 – 32.56 MJ m^{-2} day^{-1}. The estimated solar radiation values ($\widehat{RS}$) with the highest correlation (r = 0.99) with actual RS data were obtained with the RS_7 model, in which the parameters e_s, e_a, T, RH and R_a were used together. The $\widehat{RS}$ values obtained using this model varied between 6.45 to 33.99 MJ m^{-2} day^{-1}. For the RS_7, which showed the best performance among the seven models, mean absolute percentage error (MAPE) and root mean square error **(**RMSE) were determined as 4.17% and 0.69 MJ m^{-2} day^{-1}, respectively. The daily RS values measured in KSU varied between 7.75 – 33.48 MJ m^{-2} day^{-1} and 10.51 – 30.23 MJ m^{-2} day^{-1} for 2019 and 2020. The $\widehat{RS}$ values closest to the measured RS values were estimated with the RS_7 model. The estimated $\widehat{RS}$ values by this model varied between 11.74 – 33.93 MJ m^{-2} day^{-1} and 13.93 – 31.57 MJ m^{-2} day^{-1} for 2019 and 2020, respectively. MAPE values were determined as 11.33% and 7.54%, respectively. It is concluded that this model can be used to estimates daily average solar radiation and will be an excellent alternative since it is compatible with the Kahramanmaraş conditions.

Introduction

Solar radiation is the basic data of many engineering and architectural applications. Also, due to decreasing reserves of fossil fuels in the world and the environmental damages of these fuels, solar radiation as a renewable clean energy source has been increasing in importance continuously. The radiation-emitting by the sun that reaches the outer surface of the atmosphere is defined as extraterrestrial radiation. Approximately 55% of extraterrestrial radiation directly reaches the earth’s surface. This amount of radiation reaching the earth’s surface is defined as solar radiation [1].

Solar radiation is one of the most important meteorological parameters taken into account in crop production activities for agricultural purposes and in the design of agricultural structures such as greenhouses and animal barns. Also evapotranspiration, which is the most basic data of many hydrological applications such as irrigation and drainage systems, designing ponds and dams, monitoring drought, estimating the safe yield of groundwater basins and watershed management, uses approximately three-fifths of solar radiation reaching the earth [2,3].

Evapotranspiration can be estimated with various empirical methods that have been developed based on air temperature, relative humidity, wind speed and solar radiation parameters [4]. These parameters, except solar radiation, can be measured continuously and regularly in rural areas where crops are cultivated. However, solar radiation cannot be measured continuously in rural areas due to the high cost of the devices used in its measurement and difficult maintenance and calibration procedures. It can only be measured by meteorological stations located in the city centers [5]. Since solar radiation varies based on vegetation, topography, altitude, particles in the atmosphere and level of cloudiness, solar radiation data measured in city centers cannot be used in rural areas. For these reasons, there is a need to develop estimation models that can be used to determine solar radiation. Many studies have been carried out considering this need in different regions of the world. Bristow and Campbell [6], Hargreaves et al. [7], Allen [8] and Chen et al. [9] developed empirical models that can be used to estimate the amount of solar radiation based on the daily maximum and minimum air temperature and extraterrestrial radiation parameters. Ögelman et al. [10], Toğrul and Onat [11] suggested empirical models based on the daily actual (n) and maximum possible (N) sunshine hours and extraterrestrial radiation parameters. El-Sebaii et al. [5] presented a simple method to estimate solar radiation based on daily average air temperature, relative humidity and extraterrestrial radiation parameters for Jeddah, Saudi Arabia. Ertekin and Yaldız [12] developed empirical models using extraterrestrial radiation, solar declination, relative humidity, the ratio of sunshine duration (n/N), air temperature, soil temperature, cloudiness, precipitation, and evaporation for Antalya, Turkey. They showed that these models can estimate solar radiation within 2.00% mean absolute percentage error (MAPE) and 2.50 MJ m^{-2} day^{-1} root mean square error (RMSE). Trabea and Mosalam Shaltout [13] executed solar radiation estimation models using the daily actual duration of sunshine, relative humidity, maximum air temperature, the pressure measured at sea level and vapour pressure in Egyptian conditions. It was concluded that correlation coefficients ranged from 0.89 to 0.99 as an expression of the level of compatibility between the actual solar radiation data and the solar radiation values estimated using these models. El-Mghouchi et al. [14] performed a solar radiation estimation model based on altitude, latitude, and longitude parameters for Northern Morocco. This model was tested with numerical simulation and MAPE values were below 15%. Shi et al. [15] conducted a solar radiation estimation model based on some geographical and meteorological parameters in China. MAPE and RMSE were founded as 10.57% and 1.51 MJ m^{-2} day^{-1}.

The results obtained from these studies show that high accuracy solar radiation values can be estimated using empirical models that have been developed based on some meteorological and geographical parameters that can be easily measured or determined. Since solar radiation changes based on many factors, it should be either measured or estimated. It is impossible to measure solar radiation in every region and it is more economical to estimate it in an area that is needed. In this study, it is aimed to develop empirical models that can be used in the estimation of daily average solar radiation based on some parameters in Kahramanmaraş, Turkey which is located in the arid-semi arid climate zone.

Materials and Methods

Kahramanmaraş is located between the 37° 36' north latitude and 36° 55' east longitude as a geographical location. The altitude of the province is 568 m, the daily average air temperature is 16.90 ºC, relative humidity is 58.34%, the sunshine time is 6.77 hour day^{-1} and the solar radiation intensity is 4.395 kWh m^{-2} day^{-1}. The annual average daily solar radiation level is 4.40 kWh m^{-2} day^{-1}, and its distribution across the province is shown in Figure 1. The estimation models were created using the long-term average daily values of air temperature, relative humidity and solar radiation measured by Kahramanmaraş Regional Directorate of Meteorology (RDM) between 1938 – 2020. The geographical location of the RDM is 37° 34' 33" North latitude and 36° 54' 53" East longitude. The daily maximum (T_{max}, RH_{max}), minimum (T_{min}, RH_{min}) and average (T, RH) values of the air temperature and relative humidity data are given in Figure 2, Figure 3 and Figure 4, respectively. The daily solar radiation (RS) data are given in Figure 5 [16]. Long-term average daily T, RH and RS values were defined as Model Group Data (MGD).

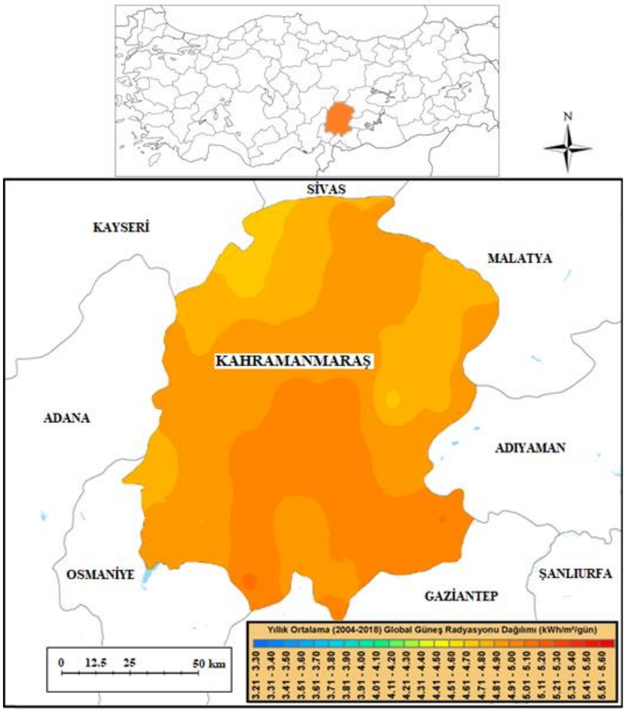

Figure 1. Annual average daily solar radiation distribution

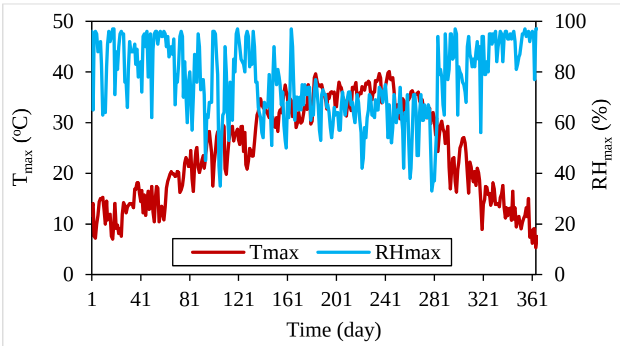

Figure 2. Daily maximum air temperature and relative humidity values for MGD

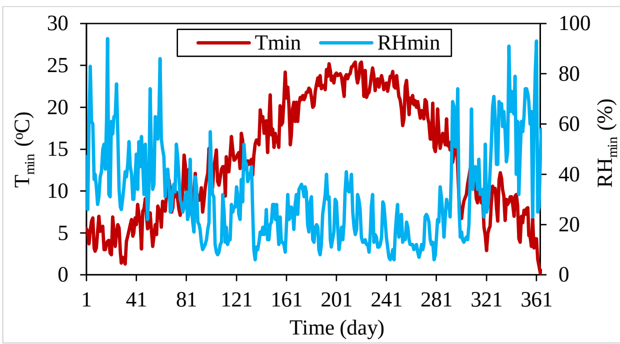

Figure 3. Daily minimum air temperature and relative humidity values for MGD

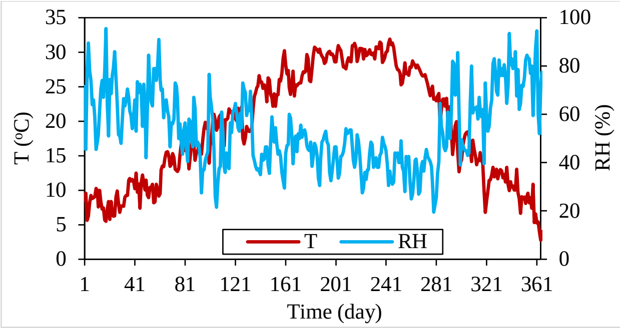

Figure 4. Daily average air temperature and relative humidity values for MGD

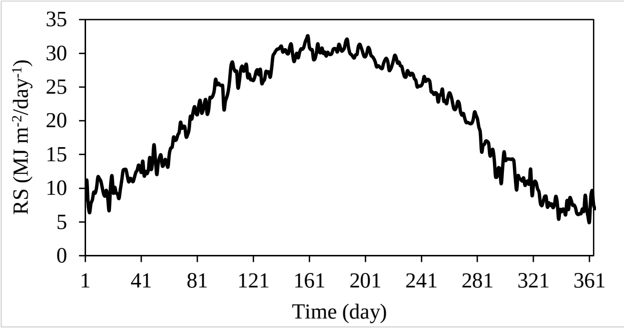

Figure 5. Daily average solar radiation values for MGD

In the study, T, RH, e_s and e_a variables were defined as meteorological parameters and also R_a as the geographical parameter. e_s and e_a values were calculated using Equations (1 – 4). R_a values were estimated by Equations (5 – 10), based on the geographical location [4,17].

$$es_{max} = 0.6108 \exp\left(\frac{17.27\ T_{max}}{T_{max} + 237.3}\right) \quad (1)$$

$$es_{min} = 0.6108 \exp\left(\frac{17.27\ T_{min}}{T_{min} + 237.3}\right) \quad (2)$$

$$e_s = \frac{es_{max} + es_{min}}{2} \quad (3)$$

$$e_a = \left[\left(\frac{es_{min}\ RH_{max}}{100}\right) + \left(\frac{es_{max} \cdot RH_{min}}{100}\right)\right] 2^{-1} \quad (4)$$

$$j = [(30.56\ \text{Month}) - 30 + \text{Day}] - 2 \quad (5)$$

$$d_r = 1 + 0.033 \cos(2.\pi.j.365^{-1}) \quad (6)$$

$$\delta = 0.409 \sin[(2.\pi.j.365^{-1}) - 1.39] \quad (7)$$

$$\emptyset = \text{Latitude}.\pi.180^{-1} \quad (8)$$

$$w_s = \arccos(-\tan\emptyset.\tan\delta) \quad (9)$$

$$R_a = 24\ \frac{60}{\pi} G_{sc}.d_r[(w_s.\sin\emptyset.\sin\delta) + (\cos\emptyset.\cos\delta.\sin w_s)] \quad (10)$$

Where; es_{max} and es_{min}, maximum and minimum saturated vapour pressures (kPa); e_s and e_a, saturated and actual vapour pressure (kPa); j, Julian date; Month, the number of the month(1 – 12); Day, the number of the day (1 – 31); d_r, inverse relative distance Earth-Sun; δ, solar declination (Radians); Latitude, latitude in degrees; Ø, latitude in radians; w_s, sunset hour angle (Radians); R_a, extraterrestrial radiation (MJ m^{-2} day^{-1}) and G_{sc}, solar constant (0.0820 MJ m^{-2} $minute^{-1}$).

Long-term average daily T, RH, RS, R_a, e_s, and e_a values used in the creation of the estimation models were defined as Model Group Data (MGD). Seven estimation models were developed by the nonlinear regression analysis method (Equation 11) using various combinations of MGD. T, RH, e_s, e_a and R_a were used as independent variables ($x_{1,i}$, $x_{2,i}$, $x_{3,i}$, $x_{4,i}$, $x_{5,i}$) and RS as dependent variable (y_i) in the creation of the models and the regression coefficients (a_0, a_1, a_2, a_3, a_4, a_5) were determined [18,19].

$$y_i = a_0.(x_{1,i})^{a1}.(x_{2,i})^{a2}.(x_{3,i})^{a3}.(x_{4,i})^{a4}.(x_{5,i})^{a5} \quad (11)$$

Equations (12 – 27) were used to determine the regression coefficients a_0, a_1, a_2, a_3, a_4 and a_5. Firstly, the logarithm of Equation (11) was taken, and given in Equation (12). Then Equation (12) was edited and written as in Equation (13). Equation (14) was written make benefit of equation (13), according to the least squares method. Equations (15 – 20) were obtained by taking partial derivatives of Equation (14) according to a_0, a_1, a_2, a_3, a_4 and a_5, respectively. Equations (15 – 20) were edited equaling zero, and thus Equations (21 – 26) were obtained. The sum of squared errors (S_r) was minimized. The matrix given in Equation (27) was obtained using Equations (21 – 26). By solving this matrix, the regression coefficients a_0, a_1, a_2, a_3, a_4 and a_5 were determined. Microsoft Excel program "solver" add-on was used to determine these coefficients.

$$\log y_i = \log a_0 + a_1 \log x_{1,i} + a_2 \log x_{2,i} + a_3 \log x_{3,i} + a_4 \log x_{4,i} + a_5 \log x_{5,i} \quad (12$$

$$y_i = a_0 + a_1 x_{1,i} + a_2 x_{2,i} + a_3 x_{3,i} + a_4 x_{4,i} + a_5 x_{5,i} \quad (13)$$

$$S_r = (y_i - a_0 - a_1 x_{1,i} - a_2 x_{2,i} - a_3 x_{3,i} - a_4 x_{4,i} - a_5 x_{5,i})^2 \quad (14)$$

$$\frac{\partial S_r}{\partial a_0} = -2\Sigma(y_i - a_0 - a_1 x_{1,i} - a_2 x_{2,i} - a_3 x_{3,i} - a_4 x_{4,i} - a_5 x_{5,i}) \quad (15)$$

$$\frac{\partial S_r}{\partial a_1} = -2\Sigma x_{1,i}(y_i - a_0 - a_1 x_{1,i} - a_2 x_{2,i} - a_3 x_{3,i} - a_4 x_{4,i} - a_5 x_{5,i}) \quad (16)$$

$$\frac{\partial S_r}{\partial a_2} = -2\Sigma x_{2,i}(y_i - a_0 - a_1 x_{1,i} - a_2 x_{2,i} - a_3 x_{3,i} - a_4 x_{4,i} - a_5 x_{5,i}) \quad (17)$$

$$\frac{\partial S_r}{\partial a_3} = -2\Sigma x_{3,i}(y_i - a_0 - a_1 x_{1,i} - a_2 x_{2,i} - a_3 x_{3,i} - a_4 x_{4,i} - a_5 x_{5,i}) \quad (18)$$

$$\frac{\partial S_r}{\partial a_4} = -2\Sigma x_{4,i}(y_i - a_0 - a_1 x_{1,i} - a_2 x_{2,i} - a_3 x_{3,i} - a_4 x_{4,i} - a_5 x_{5,i}) \quad (19)$$

$$\frac{\partial S_r}{\partial a_5}=-2\Sigma x_{5,i}\left(y_i-a_0-a_1x_{1,i}-a_2x_{2,i}-a_3x_{3,i}-a_4x_{4,i}-a_5x_{5,i}\right) \quad (20)$$

$$\Sigma y_i=\Sigma a_0+\Sigma a_1x_{1,i}+\Sigma a_2x_{2,i}+\Sigma a_3x_{3,i}+\Sigma a_4x_{4,i}+\Sigma a_5x_{5,i} \quad (21)$$

$$\Sigma x_{1,i}.y_i=\Sigma a_0\ x_{1,i}+\Sigma a_1x_{1,i}^2+\Sigma a_2x_{2,i}.x_{1,i}+\Sigma a_3x_{3,i}.x_{1,i}+\Sigma a_4x_{4,i}.x_{1,i}+\Sigma a_5x_{5,i}.x_{1,i} \quad (22)$$

$$\Sigma x_{2,i}.y_i=\Sigma a_0\ x_{2,i}+\Sigma a_1x_{1,i}.x_{2,i}+\Sigma a_2x_{2,i}^2+\Sigma a_3x_{3,i}.x_{2,i}+\Sigma a_4x_{4,i}.x_{2,i}+\Sigma a_5x_{5,i}.x_{2,i} \quad (23)$$

$$\Sigma x_{3,i}.y_i=\Sigma a_0\ x_{3,i}+\Sigma a_1x_{1,i}.x_{3,i}+\Sigma a_2x_{2,i}.x_{3,i}+\Sigma a_3x_{3,i}^2+\Sigma a_4x_{4,i}.x_{3,i}+\Sigma a_5x_{5,i}.x_{3,i} \quad (24)$$

$$\Sigma x_{4,i}.y_i=\Sigma a_0\ x_{4,i}+\Sigma a_1x_{1,i}.x_{4,i}+\Sigma a_2x_{2,i}.x_{4,i}+\Sigma a_3x_{3,i}.x_{4,i}+\Sigma a_4x_{4,i}^2+\Sigma a_5x_{5,i}.x_{4,i} \quad (25)$$

$$\Sigma x_{5,i}.y_i=\Sigma a_0\ x_{5,i}+\Sigma a_1x_{1,i}.x_{5,i}+\Sigma a_2x_{2,i}.x_{5,i}+\Sigma a_3x_{3,i}.x_{5,i}+\Sigma a_4x_{4,i}.x_{5,i}+\Sigma a_5x_{5,i}^2 \quad (26)$$

$$\begin{bmatrix}\Sigma n_{1,i}^2 & \Sigma x_{1,i}^2 & \Sigma x_{2,i}^2 & \Sigma x_{3,i}^2 & \Sigma x_{4,i}^2 & \Sigma x_{5,i}^2\\ \Sigma x_{1,i}^2 & \Sigma x_{1,i}^2 & \Sigma x_{2,i}^2.x_{1,i} & \Sigma x_{3,i}^2.x_{1,i} & \Sigma x_{4,i}^2.x_{1,i} & \Sigma x_{5,i}^2.x_{1,i}\\ \Sigma x_{2,i}^2 & \Sigma x_{1,i}^2.x_{2,i} & \Sigma x_{2,i}^2 & \Sigma x_{3,i}^2.x_{2,i} & \Sigma x_{4,i}^2.x_{2,i} & \Sigma x_{5,i}^2.x_{2,i}\\ \Sigma x_{3,i}^2 & \Sigma x_{1,i}^2.x_{3,i} & \Sigma x_{2,i}^2.x_{3,i} & \Sigma x_{3,i}^2 & \Sigma x_{4,i}^2.x_{3,i} & \Sigma x_{5,i}^2.x_{3,i}\\ \Sigma x_{4,i}^2 & \Sigma x_{1,i}^2.x_{4,i} & \Sigma x_{2,i}^2.x_{4,i} & \Sigma x_{3,i}^2.x_{4,i} & \Sigma x_{4,i}^2 & \Sigma x_{5,i}^2.x_{4,i}\\ \Sigma x_{5,i}^2 & \Sigma x_{1,i}^2.x_{5,i} & \Sigma x_{2,i}^2.x_{5,i} & \Sigma x_{3,i}^2.x_{5,i} & \Sigma x_{4,i}^2.x_{5,i} & \Sigma x_{5,i}^2\end{bmatrix}.\begin{bmatrix}\Sigma a_{0,i}^2\\ \Sigma a_{1,i}^2\\ \Sigma a_{2,i}^2\\ \Sigma a_{3,i}^2\\ \Sigma a_{4,i}^2\\ \Sigma a_{5,i}^2\end{bmatrix}=\begin{bmatrix}\Sigma y_i^2\\ \Sigma x_{1,i}^2.y_i\\ \Sigma x_{2,i}^2.y_i\\ \Sigma x_{3,i}^2.y_i\\ \Sigma x_{4,i}^2.y_i\\ \Sigma x_{5,i}^2.y_i\end{bmatrix} \quad (27)$$

The estimation models were tested using daily meteorological data measured during the July – November periods of 2019 and 2020 in the research field at KSU. The research field is 8500 meters away from the RDM. The geographical location of the research field is 37° 35' 36" North latitude and 36° 49' 20" East longitude. The daily average T, R_H, RS, e_s, e_a and R_a data measured in the research field are defined as Test Group Data (TGD). Daily T, R_H and RS data were measured using the climate station given in Figure 6. The sensors in this climate station were controlled by the Programmable Logic Controller (PLC) device. A software was prepared using the CODESYS structured text (ST) programming language and was loaded into PLC. Daily T, RH and RS data were measured by sensors via this software and recorded on the SD card.

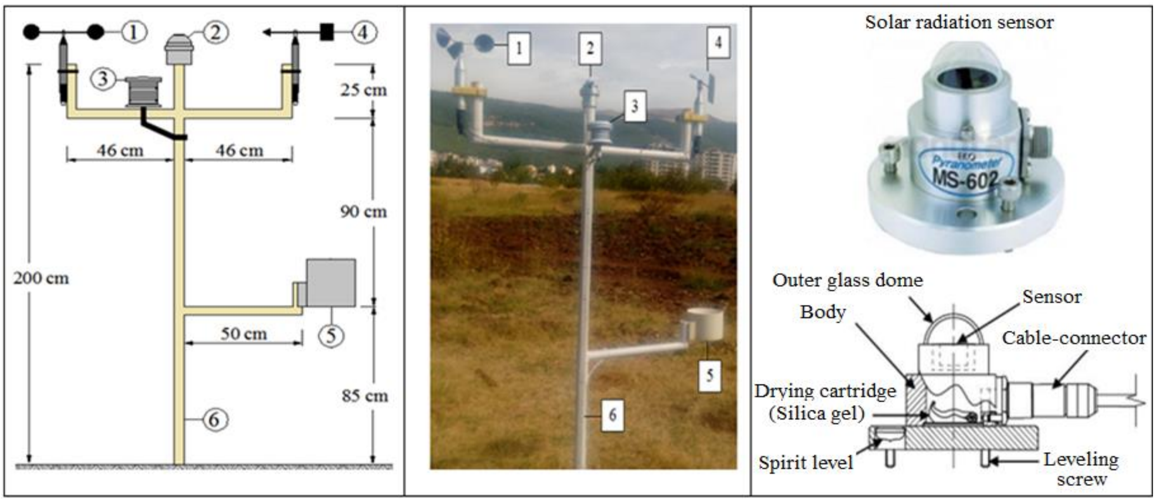

Figure 6. PLC controlled climate station: 1, wind speed sensor; 2, solar radiation sensor (pyranometer); 3, air temperature and humidity sensors; 4, wind direction sensor; 5, precipitation sensor; 6, platform

The MAE, MAPE and RMSE error values were considered as an expression of deviation amounts between estimated $\widehat{RS}$ values and actual RS data. These error values were calculated using Equations (28 – 30) [20]. Lewis's [20] interpretation of MAPE results is a means to judge the accuracy of the estimate—less than 10% is a "excellent" estimate, 10% to 20% is a "good" estimate, 20% to 50% is a "reasonable" estimate, and 50% or more is an "inaccurate" estimate.

$$\mathrm{MAE}=\frac{1}{n}\sum_{i:1}^{n}\left(|RS_i-\widehat{RS}_i|\right) \quad (28)$$

$$\mathrm{MAPE}=\frac{1}{n}\sum_{i:1}^{n}\left(\frac{|RS_i-\widehat{RS}_i|}{RS_i}100\right) \quad (29)$$

$$\mathrm{RMSE}=\sqrt{\frac{1}{n}\sum_{i:1}^{n}\left(RS_i-\widehat{RS}_i\right)^2} \quad (30)$$

Where; MAE, mean absolute error (MJ m^{-2} day^{-1}); MAPE, mean absolute percentage error (%); RMSE, root mean square error (MJ m^{-2} day^{-1}); RS_i and $\widehat{RS}_i$, actual and estimated solar radiation values (MJ m^{-2} day^{-1}); and n, is the number of observations.

Results and Discussion

Firstly e_s, e_a and R_a values were calculated using MGD. Then, estimation models were created using the nonlinear regression analysis method and given in Table 1. Correlation (r) and determination (R^2) coefficients, and MAE, MAPE, and RMSE values of the models were determined in order to reveal the statistical relationship levels between the estimated $\widehat{RS}$ values using the models and the actual RS data measured by the RDM (Table 2). The daily average actual RS data measured by RDM varied between 4.99 – 32.56 MJ m^{-2} day^{-1}.

Table 1. Solar radiation estimation models

Model	Estimation equation
RS_1	$\widehat{RS} = 410.8045\ RH^{-0.769}$
RS_2	$\widehat{RS} = 1.8583\ T^{0.813}$
RS_3	$\widehat{RS} = 0.2818\ R_a^{1.262}$
RS_4	$\widehat{RS} = 0.3175\ T^{0.197}\ R_a^{1.056}$
RS_5	$\widehat{RS} = 1.0948\ RH^{-0.263}\ R_a^{1.164}$
RS_6	$\widehat{RS} = 0.9569\ T^{0.067}\ RH^{-0.229}\ R_a^{1.106}$
RS_7	$\widehat{RS} = 0.4169\ e_s^{-0.121}\ e_a^{-0.077}\ T^{0.302}\ RH^{-0.144}\ R_a^{1.084}$

Table 2. The statistical relationships between actual and estimated solar radiation values for MGD

Model	r	R^2	MAE (MJ m^{-2} day^{-1})	MAPE (%)	RMSE (MJ m^{-2} day^{-1})	Accuracy
RS_1	0.58	0.33	5.70	37.40	6.50	Reasonable
RS_2	0.85	0.72	3.64	22.84	4.26	Reasonable
RS_3	0.96	0.93	1.30	8.86	1.60	Excellent
RS_4	0.98	0.95	0.99	7.17	1.25	Excellent
RS_5	0.99	0.97	0.62	4.85	0.81	Excellent
RS_6	0.99	0.97	0.57	4.62	0.75	Excellent
RS_7	0.99	0.98	0.49	4.17	0.69	Excellent

The $\widehat{RS}$ values with the highest correlation with actual RS data were estimated by RS_3, RS_4, RS_5, RS_6 and RS_7 models. Correlation coefficients of these models varied between 0.96 – 0.99. R_a was used as the common independent variable in all of these models. The accuracy level of the $\widehat{RS}$ values estimated using these models was determined as “excellent” (MAPE<10%). As it is seen in Figure 7, the $\widehat{RS}$ values estimated by RS_5, RS_6 and RS_7 models having the lowest MAE, MAPE and RMSE values almost completely overlapped with the actual RS values. The $\widehat{RS}$ values estimated using these models varied between 7.88 – 34.59 MJ m^{-2} day^{-1}, 7.68 – 34.38 MJ m^{-2} day^{-1} and 6.45 – 33.99 MJ m^{-2} day^{-1}, respectively. The $\widehat{RS}$ values closest to the actual RS data realized at the annual average 20.18 MJ m^{-2} day^{-1} level were estimated using RS_5, RS_6 and RS_7 models. The annual average values for these models were determined as 21.16 MJ m^{-2} day^{-1}, 21.11 MJ m^{-2} day^{-1} and 21.02 MJ m^{-2} day^{-1}, respectively. Among the seven estimation models, the lowest MAPE (4.17%) and RMSE (0.69 MJ m^{-2} day^{-1}) values were obtained with the RS_7 models.

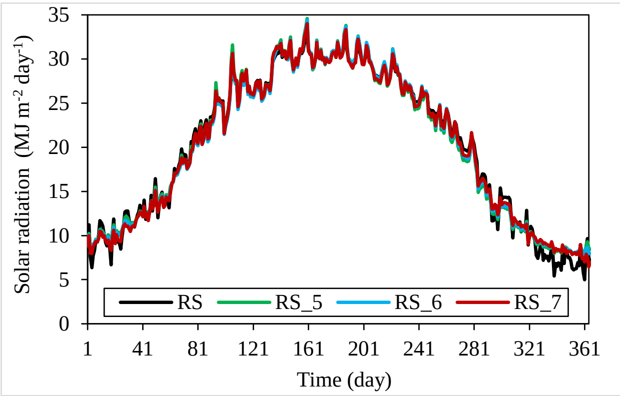

Figure 7. Daily average RS and $\widehat{RS}$ values for MGD

It was observed that as the number of independent variables used in the estimation models increased, the accuracy level of the $\widehat{RS}$ values increased, while the MAE, MAPE and RMSE decreased. Since RH and T parameters are used as the single independent variable in the RS_1 and RS_2 models, correlation coefficients (0.58 – 0.85) were lower than those other models using the R_a parameter. The accuracy level of the $\widehat{RS}$ values estimated using these models were determined as “reasonable” (MAPE= 20 – 50%). The lowest correlation (r= 0.58) and determination (R^2= 0.33) coefficients among the seven estimation models were obtained by the RS_1 model, whose independent variable was RH. The highest MAPE (37.40%) and RMSE (6.50 MJ m^{-2} day^{-1}) were obtained by this model. Similarly, Deniz and Atik [21] and Ayegba et al. [22] determined the correlation coefficients as 0.43 and 0.48 respectively for the single variable solar radiation estimation models developed using the RH parameter. It was observed that T has higher correlation (r= 0.85) with RS than RH. The determination coefficient, MAPE and RMSE values were obtained as 0.72, 22.84% and 4.26 MJ m^{-2} day^{-1}, respectively for the RS_2 model whose single independent variable was T. The accuracy of the $\widehat{RS}$ values estimated with the RS_3 model, in which the R_a parameter were used as the only independent variable, was higher than the RS_2 model. For this model, the determination coefficient, MAPE and RMSE values were determined as 0.93, 8.86% and 1.60 MJ m^{-2} day^{-1}, respectively. The determination coefficient, MAPE and RMSE values for the RS_4 model, in which the daily T and R_a parameters were used as independent variables, were determined as 0.95, 7.17% and 1.25 MJ m^{-2} day^{-1}, respectively. Similarly, Ertekin and Yaldız [12] developed an estimation model based on daily average T and R_a parameters. Tabari et al. [23] were tested this model under arid and semi-arid conditions in Iran. The determination coefficients and RMSE values determined as an expression of the deviation between the estimated $\widehat{RS}$ values using this model and the actual RS values varied between 0.71 – 0.75, and 3.69 – 6.78 MJ m^{-2} day^{-1}, respectively. Hargreaves et al. [7], Allen [8] and Chen et al. [9] developed estimation models based on the daily T_{max}, T_{min} and R_a parameters. Alsamamra [24] was tested these models in Palestine. The MAPE and RMSE values determined for these models varied between, 0.66 – 9.12% and 0.71 – 0.92 MJ m^{-2} day^{-1}, respectively.

The main factors determining the amount of RS reaching the earth surface are the clearness index of the atmosphere resulting from the cloud density, and the water vapour content in the atmosphere. It is known that the source of the water vapour and the clouds are evaporation, and evaporation is related to T and RH. Ye and Fetzer [25] stated that the water vapour content in the atmosphere and therefore the RH changes based on the T, and decreases with the increasing T. The decrease in water vapour causes to decrease the amount of R_a absorbed or reflected by the water vapour and clouds, and therefore increase the amount of RS reaching the earth. It is seen that there is a strong relationship between T, RH and R_a parameters and the RS. For the RS_5 model in which RH and R_a were used as independent variables together, the determination coefficient, MAPE and RMSE values were determined as 0.97, 4.85% and 0.85 MJ m^{-2} day^{-1}, respectively. The accuracy of the $\widehat{RS}$ values estimated by the RS_6 model, in which the T, RH and R_a parameters were used together as independent variables, were higher than the RS_5. For this model, the determination coefficient, MAPE and RMSE values were determined as 0.97%, 4.62% and 0.75 MJ m^{-2} day^{-1}, respectively. Similarly, El-Sebaii et al. [5] developed an estimation model based on daily T, RH and R_a parameters. Tabari et al. [23] were tested this model under semi-arid conditions in Iran. The determination coefficients and RMSE values determined for this model varied between, 0.036 – 0.174, and 7.34 – 13.45 MJ m^{-2} day^{-1}, respectively. It has been observed that this model created in Saudi Arabia conditions is not suitable for Iran. Penman [26] and Monteith [27] reported that the vapour pressure deficit (e_s – e_a) in the atmosphere is directly related to RH and "e_s – e_a" increased as the RH decreased. Therefore, the accuracy of the $\widehat{RS}$ values estimated by RS_7 model in which es and ea independent variables were used in addition to T, RH and R_a was higher than RS_6 model. Şarlak and Güven [28] realized a multivariate solar radiation estimation model with linear regression analysis by together using the parameters e_s, e_a, T, RH and wind speed in Gaziantep, Turkey. It was stated that 75.70% of the observed change in actual solar radiation data explained by this model (R^2= 0.76). Similarly, the determination coefficient for the RS_7 model, in which the same parameters except wind speed were used as independent variables, was obtained as 0.98. In this model, R_a was used instead of wind speed.

To test the usability of estimation models in different regions, TGD measured in the research field was used. T_{max}, T_{min}, T, RH_{max}, RH_{min} and RH data were measured in the research field in the 2019 and 2020, were given in Figure 8 and Figure 9, respectively. R_a, e_s and e_a values were determined based on these meteorological data and the geographical location of the research field. The daily average actual RS data measured in research field in 2019 and 2020 varied between in the 7.75 – 33.48 MJ m^{-2} day^{-1} and 10.51 – 30.23 MJ m^{-2} day^{-1} (Figure 10).

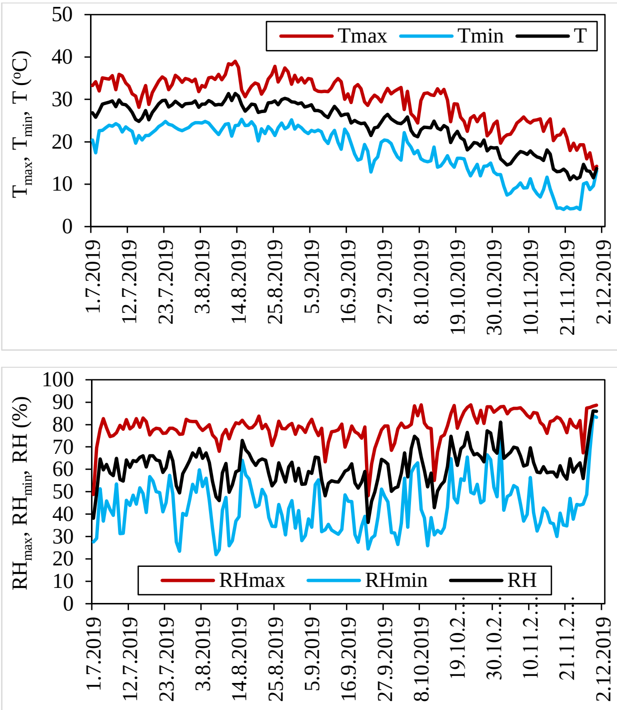

Figure 8. Daily maximum, minimum, average air temperature and relative humidity values for TGD (2019)

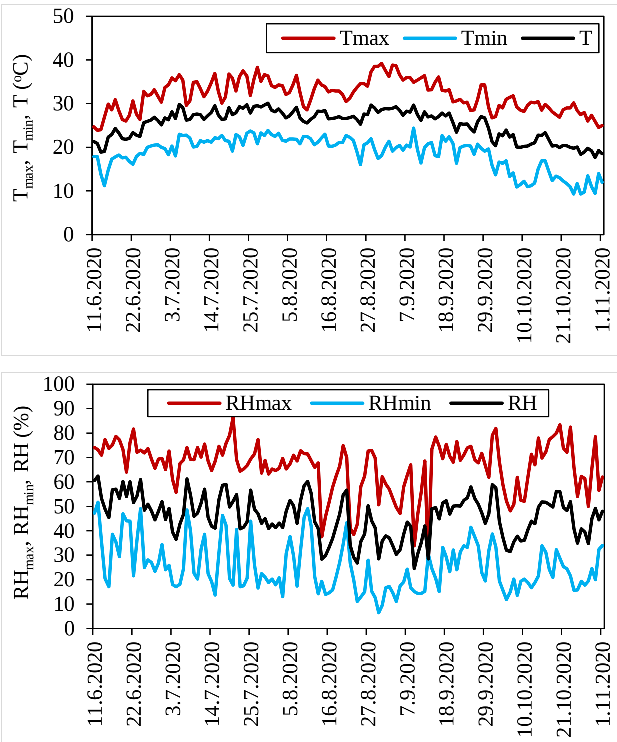

Figure 9. Daily maximum, minimum, average air temperature and relative humidity values for TGD (2020)

T, RH, e_s, e_a and R_a data were substituted in the estimation model equations and $\widehat{RS}$ values were determined for each model. MAE, MAPE and RMSE error values were determined as an expression of the deviation amounts between estimated $\widehat{RS}$ values and actual RS data (Table 3).

Table 3. The statistical relationships between actual and estimated solar radiation values for TGD

Model	MAE (MJ m^{-2} day^{-1})		MAPE (%)		RMSE (MJ m^{-2} day^{-1})		Accuracy	
	2019	2020	2019	2020	2019	2020	2019	2020
RS_1	6.05	6.06	35.31	27.78	7.14	6.93	Reasonable	Reasonable
RS_2	4.65	4.24	34.68	21.95	5.59	5.04	Reasonable	Reasonable
RS_3	1.83	1.51	13.03	6.58	2.38	1.93	Good	Excellent
RS_4	2.05	1.81	14.31	8.05	2.69	2.21	Good	Excellent
RS_5	1.68	1.54	11.98	6.98	2.13	2.12	Good	Excellent
RS_6	1.53	1.63	11.48	7.42	2.05	2.19	Good	Excellent
RS_7	1.47	1.62	11.33	7.54	2.13	2.15	Good	Excellent

Similarly, RDM data, it was seen that the models with the lowest error values with the actual RS data were RS_5, RS_6 and RS_7 models. The $\widehat{RS}$ values estimated using these models varied between 11.05 – 36.54 MJ m^{-2} day^{-1}, 11.40 – 35.76 MJ m^{-2} day^{-1}, 11.74 – 33.93 MJ m^{-2} day^{-1}, respectively, in 2019, and varied between 13.40 – 31.87 MJ m^{-2} day^{-1}, 13.65 – 31.83 MJ m^{-2} day^{-1}, 13.93 – 31.57 MJ m^{-2} day^{-1}, respectively, in 2020 (Figure 10).

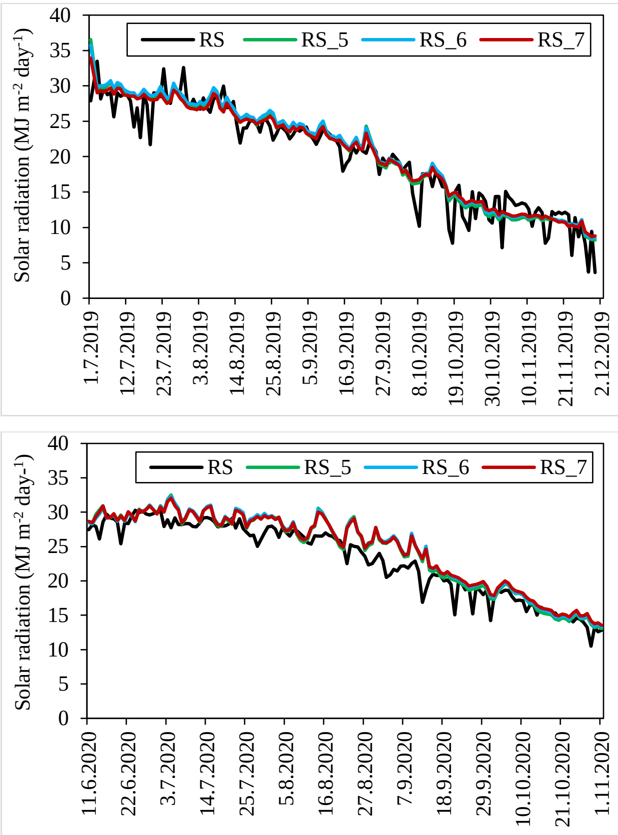

Figure 10. Daily average RS and $\widehat{RS}$ values for TGD

Although there are differences between the maximum and minimum points of the $\widehat{RS}$ and RS graphs, it is clearly seen in figure 8 that they generally move synchronized. The $\widehat{RS}$ values closest to the actual RS data, which were realized at the average 22.48 MJ m^{-2} day^{-1} and 22.27 MJ m^{-2} day^{-1} levels in the July – October periods of 2019 and 2020, respectively, were estimated using the RS_5, RS_6 and RS_7 models. The average $\widehat{RS}$ values for these models in 2019 were determined as 24.22 MJ m^{-2} day^{-1}, 23.50 MJ m^{-2} day^{-1} and 21.69 MJ m^{-2} day^{-1}, respectively. The same values were obtained as 23.82 MJ m^{-2} day^{-1}, 23.92 MJ m^{-2} day^{-1} and 23.95 MJ m^{-2} day^{-1} for 2020, respectively. The accuracy level of $\widehat{RS}$ values estimated using RS_5, RS_6 and RS_7 models were determined as "good" in 2019 (MAPE= 10 – 20%) and as "excellent" in 2020 (MAPE<10%).

Conclusions

In this study, seven solar radiation estimation models were developed with nonlinear regression analysis method by creating various combinations of daily average T, RH, R_a, e_s and e_a parameters. The models were created using long-term average daily meteorological data measured by Kahramanmaraş Regional Directorate of Meteorology (RDM) between 1938 – 2018 and tested using daily meteorological data measured at the Kahramanmaraş Sütçü İmam University (KSU) campus in 2019 and 2020. According to both RDM and KSU data, the closest values to the actual RS data was estimated with the RS_7 model ($\widehat{RS} = 0.4169\, e_s^{-0.121}\, e_a^{-0.077}\, T^{0.302}\, RH^{-0.144}\, R_a^{1.084}$). The daily average actual RS data measured by RDM varied between 4.99 – 32.56 MJ m^{-2} day^{-1}. The $\widehat{RS}$ values with the highest correlation with actual RS data was estimated by RS_7 model. The $\widehat{RS}$ values estimated using this model varied between 6.45 – 33.99 MJ m^{-2} day^{-1}. The ratio in which the change in actual RS values can be explained by the RS_7 model was obtained as 98% (R^2= 0.98). According to RDM data, MAPE was determined as 4.17% as an expression of the deviation amounts of $\widehat{RS}$ values estimated by RS_7 from actual RS data. According to the 2019 and 2020 data measured at the KSU, the MAPE values for RS_7 were obtained as 11.33% and 7.54%, respectively. The accuracy level of $\widehat{RS}$ values estimated using RS_7 model was determined as "good" in 2019 (MAPE= 10 – 20%) and as "excellent" in 2020 (MAPE<10%). It is concluded that the RS_7 model can be used to estimates daily average solar radiation and will be an excellent alternative since it is compatible with the Kahramanmaraş conditions.

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