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Empirical models for estimating global solar radiation: A review and case study

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ABSTRACT

Solar radiation is a primary driver for many physical, chemical, and biological processes on the earth's surface. Solar energy engineers, architects, agriculturists, hydrologists, etc. often require a reasonably accurate knowledge of the availability of the solar resource for their relevant applications at their local. In solar applications, one of the most important parameters needed is the long-term average daily global irradiation. For regions where no actual measured values are available, a common practice is to estimate average daily global solar radiation using appropriate empirical correlations based on the measured relevant data at those locations. These correlations estimate the values of global solar radiation for a region of interest from more readily available meteorological, climatological, and geographical parameters. The main objective of this study is to chronologically collect and review the extensive global solar radiation models available in the literature and to classify them into four categories, i.e., sunshine-based, cloud-based, temperature-based, and other meteorological parameter-based models, based on the employed meteorological parameters as model input.

Furthermore, in order to evaluate the accuracy and applicability of the models reported in this paper for computing the monthly average daily global solar radiation on a horizontal surface, the geographical and meteorological data of Yazd city, Iran was used. The developed models were then evaluated and compared on the basis of statistical error indices and the most accurate model was chosen in each category. Results revealed that all the proposed correlations have a good estimation of the monthly average daily global solar radiation on a horizontal surface in Yazd city, however, the El-Metwally sunshine-based model predicts the monthly averaged global solar radiation with a higher accuracy.

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1. Introduction

Solar radiation arriving on earth is the most fundamental renewable energy source in nature. Solar energy, radiant light and heat from the sun, has been harnessed by humans since ancient times using a range of ever evolving technologies. The energy from the sun could play a key role in de-carbonizing the global economy alongside improvements in energy efficiency and imposing costs on greenhouse gas emitters. In the studies of solar energy, data on solar radiation and its components at a given location are a fundamental input for solar energy applications such as photovoltaic, solar-thermal systems, solar furnaces and passive solar design. The data should be reliable and readily available for design, optimization and performance evaluation of solar systems for any particular location. The best way to determine the amount of global solar radiation at any site is to install measuring instruments such as pyranometer and pyrheliometer at that particular place and to monitor and record its day-to-day recording, which is really a very tedious and costly exercise [1]. In spite of the importance of solar radiation measurements, in many developing countries this information is not readily available because of not being able to afford the measuring equipments and techniques involved. Therefore, a number of correlations and methods have been developed to estimate daily or monthly global solar radiation on the basis of the more readily available meteorological data at a majority of weather stations. Empirical models which have been used to calculate solar radiation are usually based on the following factors [2]:

(1) Astronomical factors (solar constant, earth-sun distance, solar declination and hour angle).
(2) Geographical factors (latitude, longitude and elevation of the site).
(3) Geometrical factors (azimuth angle of the surface, tilt angle of the surface, sun elevation angle, sun azimuth angle).
(4) Physical factors (scattering of air molecules, water vapor content, scattering of dust and other atmospheric constituents such as O_2, N_2, CO_2, O, etc.).
(5) Meteorological factors (extraterrestrial solar radiation, sunshine duration, temperature, precipitation, relative humidity, effects of cloudiness, soil temperature, evaporation, reflection of the environs, etc.).

The number of correlation that have been published and tested to estimate the monthly average daily global solar radiation is relatively high, which makes it difficult to choose the most appropriate method for a particular purpose and site. Selecting an appropriate methods from various existing models is based on their data requirements (the selected methods utilize only daily variables normally available at a majority of weather stations) and the model accuracy.

Estimations of the monthly mean daily global solar radiation for a large number of locations are presented in various research works. The main objective of this study is to comprehensively collect and present the global solar radiation models available in the literature, including the study carried out on the estimation of the monthly average daily global solar radiation on horizontal surfaces and to classify them into four categories based on the employed meteorological parameters as model inputs. It is noteworthy that all the proposed models contain empirical constants which depend on the season and the geographical location of a particular place. The empirical coefficients for some correlations available in the literature are presented. The models collected and reviewed in this research are chronologically presented and therefore are useful for selecting the appropriate model to estimate global solar radiation for a particular place of interest.

In addition, in order to evaluate the performance of the models in each of the four categories described in Section 2, some selected models from each category are used to estimate the monthly average daily global solar radiation by using, astronomical, geographical, geometrical and meteorological data of Yazd city, Iran. The solar radiation values produced by the selected models are then compared with each other as well as with the available experimental data. Among the selected models in each category, the model which produces the most accurate values of global solar radiation is selected and used for predicting the monthly average daily global solar radiation in Yazd.

2. Modeling of global solar radiation

Solar researchers have developed many empirical correlations which determine the relation between solar radiation and various meteorological parameters. As the availability of meteorological parameters, which are used as the input of radiation models is the most important key to choose the proper radiation models at any location, empirical models can be mainly classified into four following categories based on the employed meteorological parameters:

(1) Sunshine-based models.
(2) Cloud-based models.
(3) Temperature-based models.
(4) Other meteorological parameter-based models.

Among all such meteorological parameters, bright sunshine hours, cloud cover and temperature are the most widely and commonly used ones to predict global solar radiation and its components at any location of interest.

2.1. Sunshine-based models

The most commonly used parameter for estimating global solar radiation is sunshine duration. Sunshine duration can be easily and reliably measured, and data are widely available at the weather stations. Most of the models for estimating solar radiation that appear in the literature only use sunshine ratio (S/S_0) for prediction of monthly average daily global radiation. In the following section, correlations which use only the sunshine ratio as the key input parameter are presented and classified based on their developing year.

2.1.1. Model 1: Angström–Prescott model

The first and the most widely used correlation for estimating monthly average daily global solar radiation was proposed by Angström [3], who derived a linear relationship between the ratio

Nomenclature

a–t	regression coefficients
C	mean total cloud cover during daytime observations (octa)
CF	cloud factor
E	mean evaporation (cm)
H	monthly average daily global radiation on horizontal surface (MJ/m^2 day)
H_0	monthly average daily extraterrestrial radiation on horizontal surface (MJ/m^2 day)
H_c	monthly average clear sky daily global radiation on horizontal surface (MJ/m^2 day)
H_b	monthly average daily beam radiation on horizontal surface (MJ/m^2 day)
H_d	monthly average daily diffuse radiation on horizontal surface (MJ/m^2 day)
H_{mod}	the estimated global solar radiation corrected for systematic bias (MJ/m^2 day)
H_{day}	half-day length
I_b	hourly beam radiation (MJ/m^2 h)
I_d	hourly diffuse radiation (MJ/m^2 h)
I_{sc}	solar constant (1367 W/m^2)
n	number of day of year starting from the first of January
P	mean precipitation
p_0	atmospheric pressure at sea level (hpa)
p_s	atmospheric pressure at the site (hpa)
PS	ratio between mean sea level pressure and mean daily vapor pressure
PWV	precipitable water vapor (mm)
RH	mean relative humidity (%)
RH_{max}	maximum relative humidity (%)
S	monthly average daily bright sunshine duration (h)
S_0	monthly average maximum possible daily sunshine duration (h)
S_{nh}	sunshine duration that take into account the natural horizon of the site (h)
ST	mean soil temperature (°C)
T	mean air temperatures (°C)
T_K	mean air temperature (K)
T_{max}	mean maximum daily temperatures (°C)
T_{min}	mean minimum daily temperatures (°C)
ΔT	Temperature difference (°C)
ΔT_m	monthly mean ΔT (°C)
t_d	mean dew point temperature (°C)
V	mean water vapor pressure (hpa)
w	atmospheric precipitable water vapor per unit volume of air (cm)
Z	altitude of site (km)
$e_S(T)$	saturation vapor pressure at the air temperature T (kPa)

Greek letters

δ	solar declination (°)
θ	solar zenith angle (°)
φ	latitude of the location (°)
L	latitude of the location (rad)
λ	longitude of the location (°)
ω_s	sunset hour angle (°)
h_α	the noon solar altitude angle of the sun (°)
τ	atmospheric transmittance
$\tau_{t,\mathrm{max}}$	maximum (cloud-free) daily total transmittance at a location
$\tau_{f,\mathrm{max}}$	proportion of $\tau_{t,\mathrm{max}}$ observed on a given day (cloud correction)

of average daily global radiation to the corresponding value on a completely clear day (H/H_c) at a given location and the ratio of average daily sunshine duration to the maximum possible sunshine duration.

$$\frac{H}{H_C} = a + b\left(\frac{S}{S_0}\right) \tag{1}$$

A basic difficulty with Eq. (1) lies in the definition of the term H_c. Prescott [4] and the others have modified the method to base it on extraterrestrial radiation on a horizontal surface rather than on clear day radiation and therefore proposed the following relation:

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) \tag{2}$$

The values of the monthly average daily extraterrestrial irradiation (H_0) can be calculated from the following equation [5]:

$$H_0\left(\frac{Wh}{m^2\ day}\right) = \frac{24}{\pi} I_{sc}\left[1 + 0.033\ cos\left(\frac{360n}{365}\right)\right]\left[cos\varphi\ cos\delta\ sin\omega_s + \frac{\pi}{180}\omega_s\ sin\varphi\ sin\delta\right] \tag{3}$$

The solar declination (δ) and the mean sunrise hour angle (ω_s) can be calculated by following equations [5]:

$$\delta = 23.45\ sin\left[\frac{360}{365}(284 + n)\right] \tag{4}$$

$$\omega_s = cos^{-1}(-tan\varphi\ tan\delta) \tag{5}$$

For a given month, the maximum possible sunshine duration (monthly average day length, S_0) can be computed by using the following equation [5]:

$$S_0 = \frac{2}{15}\omega_s \tag{6}$$

Although the Angström–Prescott [4] equation can be improved to produce more accurate results, it is used as such for many applications. Some of the regression models based on the Angström–Prescott model which proposed in literature are given as follows:

– Jain model for Italy [6]

$$\frac{H}{H_0} = 0.177 + 0.692\left(\frac{S}{S_0}\right) \tag{7}$$

– El-Metwally model for Egypt [7]

$$\frac{H}{H_0} = 0.228 + 0.527\left(\frac{S}{S_0}\right) \tag{8}$$

– Bakirci model for Turkey [8]

$$\frac{H}{H_0} = 0.2786 + 0.4160\left(\frac{S}{S_0}\right) \tag{9}$$

– Alsaad model for Amman, Jordan [9]

$$\frac{H}{H_0} = 0.174 + 0.615\left(\frac{S}{S_0}\right) \tag{10}$$

– Jain and Jain model for Zambian [10]

$$\frac{H}{H_0} = 0.240 + 0.513\left(\frac{S}{S_0}\right) \quad (11)$$

– Katiyar et al. model for India [1]

$$\frac{H}{H_0} = 0.2281 + 0.5093\left(\frac{S}{S_0}\right) \quad (12)$$

– Lewis model for state of Tennessee, U.S.A. [11]

$$\frac{H}{H_0} = 0.14 + 0.57\left(\frac{S}{S_0}\right) \quad (13)$$

– Tiris et al. model for Turkey [12]

$$\frac{H}{H_0} = 0.18 + 0.62\left(\frac{S}{S_0}\right) \quad (14)$$

– Almorox and Hontoria model for Spain [13]

$$\frac{H}{H_0} = 0.2170 + 0.5453\left(\frac{S}{S_0}\right) \quad (15)$$

– Raja and Twidell model for Pakistan [14,15]

$$\frac{H}{H_0} = 0.335 + 0.367\left(\frac{S}{S_0}\right) \quad (16)$$

– Li et al. model for Tibet, China [16]

$$\frac{H}{H_0} = 0.2223 + 0.6529\left(\frac{S}{S_0}\right) \quad (17)$$

– Said et al. model for Tripoli, Libya [17]

$$\frac{H}{H_0} = 0.215 + 0.527\left(\frac{S}{S_0}\right) \quad (18)$$

– Ulgen and Ozbalta model for Izmir-Bornova, Turkey [18]

$$\frac{H}{H_0} = 0.2424 + 0.5014\left(\frac{S}{S_0}\right) \quad (19)$$

– El-Sebaii et al. model For Jeddah, Saudi Arabia [19]

$$\frac{H}{H_0} = -2.81 + 3.78\left(\frac{S}{S_0}\right) \quad (20)$$

– Rensheng et al. model for 86 stations in China [20]

$$\frac{H}{H_0} = 0.176 + 0.563\left(\frac{S}{S_0}\right) \quad (21)$$

– Ahmad and Ulfat model for Karachi, Pakistan [21]

$$\frac{H}{H_0} = 0.324 + 0.405\left(\frac{S}{S_0}\right) \quad (22)$$

– Jin et al. model for 69 stations in China [22]

$$\frac{H}{H_0} = 0.1332 + 0.6471\left(\frac{S}{S_0}\right) \quad (23)$$

– Akpabio and Etuk model for Onne region (within the rainforest climatic zone of southern Nigeria) [23]

$$\frac{H}{H_0} = 0.23 + 0.38\left(\frac{S}{S_0}\right) \quad (24)$$

– Ulgen and Hepbasli model for Ankara, Istanbul and Izmir in Turkey [24]

$$\frac{H}{H_0} = 0.2671 + 0.4754\left(\frac{S}{S_0}\right) \quad (25)$$

– Aras et al. model for twelve provinces in the Central Anatolia Region of Turkey [25]

$$\frac{H}{H_0} = 0.3078 + 0.4166\left(\frac{S}{S_0}\right) \quad (26)$$

– Togrul and Togrul model for Ankara, Antalya, Izmir, Yenihisar (Aydin), Yumurtalik (Adana) and Elazig in Turkey [26]

$$\frac{H}{H_0} = 0.318 + 0.449\left(\frac{S}{S_0}\right) \quad (27)$$

– Kholagi et al. model for three different stations in Yemen [27]

$$\frac{H}{H_0} = -0.191 + 0.571\left(\frac{S}{S_0}\right) \quad (28a)$$

$$\frac{H}{H_0} = 0.297 + 0.432\left(\frac{S}{S_0}\right) \quad (28b)$$

$$\frac{H}{H_0} = 0.262 + 0.454\left(\frac{S}{S_0}\right) \quad (28c)$$

– Katiyar et al. model for Jodhpur, Calcutta, Bombay, Pune in India, respectively [1]

$$\frac{H}{H_0} = 0.2276 + 0.5105\left(\frac{S}{S_0}\right) \quad (29a)$$

$$\frac{H}{H_0} = 0.2623 + 0.3952\left(\frac{S}{S_0}\right) \quad (29b)$$

$$\frac{H}{H_0} = 0.2229 + 0.5123\left(\frac{S}{S_0}\right) \quad (29c)$$

$$\frac{H}{H_0} = 0.2286 + 0.5309\left(\frac{S}{S_0}\right) \quad (29d)$$

– Jain model for (Salisbury, Bulawayo and Macerata, Italy), respectively [28]

$$\frac{H}{H_0} = 0.313 + 0.474\left(\frac{S}{S_0}\right) \quad (30a)$$

$$\frac{H}{H_0} = 0.307 + 0.488\left(\frac{S}{S_0}\right) \quad (30b)$$

$$\frac{H}{H_0} = 0.309 + 0.599\left(\frac{S}{S_0}\right) \quad (30c)$$

– Veeran and Kumar model for two tropical locations Madras and Kodaikanal in India, respectively [29]

$$\frac{H}{H_0} = 0.34 + 0.32\left(\frac{S}{S_0}\right) \quad (31a)$$

$$\frac{H}{H_0} = 0.27 + 0.65\left(\frac{S}{S_0}\right) \quad (31b)$$

– Chegaar and Chibani model for Algiers and Oran, Beni Abbas and Tamanrasset, Algeria [30]

$$\frac{H}{H_0} = 0.309 + 0.368\left(\frac{S}{S_0}\right) \quad (32a)$$

$$\frac{H}{H_0} = 0.367 + 0.367\left(\frac{S}{S_0}\right) \tag{32b}$$

$$\frac{H}{H_0} = 0.233 + 0.591\left(\frac{S}{S_0}\right) \tag{32c}$$

– Ampratwum and Dorvlo model for Seeb and Sallalah weather stations in Oman, respectively [31]

$$\frac{H}{H_0} = 0.3326 + 0.3110\left(\frac{S}{S_0}\right) \tag{33a}$$

$$\frac{H}{H_0} = 0.2418 + 0.3555\left(\frac{S}{S_0}\right) \tag{33b}$$

2.1.2. Model 2: Glower and McCulloch model

Glower and McCulloch proposed the following equation, which takes into account the effect of latitude of the site, φ, as an additional input and is valid for $(\varphi < 60^\circ)$[32]:

$$\frac{H}{H_0} = a\,cos\varphi + b\left(\frac{S}{S_0}\right) \tag{34a}$$

$$\frac{H}{H_0} = 0.29\,cos\varphi + 0.52\left(\frac{S}{S_0}\right) \tag{34b}$$

Some other corresponding modified relations are:

– Ulgen and Hepbasli model for Izmir, Turkey [33]

$$\frac{H}{H_0} = 0.3092\,cos\varphi + 0.4931\left(\frac{S}{S_0}\right) \tag{35}$$

– Raja and Twidell model for Pakistan [14,15]

$$\frac{H}{H_0} = 0.388\,cos\varphi + 0.367\left(\frac{S}{S_0}\right) \tag{36a}$$

$$\frac{H}{H_0} = 0.388\,cos\varphi + 0.407\left(\frac{S}{S_0}\right) \tag{36b}$$

2.1.3. Model 3: Page model

Page has provided the coefficients of the modified Angström-type model [4], which is claimed to be applicable anywhere in the world [34]:

$$\frac{H}{H_0} = 0.23 + 0.48\left(\frac{S}{S_0}\right) \tag{37}$$

2.1.4. Model 4: Rietveld model

Rietveld by using measured data collected from 42 stations located in different countries, has proposed a unified correlation to compute the horizontal global solar radiation. Rietveld's model, which is claimed to be applicable anywhere in the world, is given in following equation [35]:

$$\frac{H}{H_0} = 0.18 + 0.62\left(\frac{S}{S_0}\right) \tag{38}$$

Rietveld also examined several published values of a and b coefficients of the Angström–Prescott model [4] and noted that constants a and b are related linearly to the appropriate mean value of S/S_0 as follows [35]:

$$a = 0.10 + 0.24\left(\frac{S}{S_0}\right) \tag{39a}$$

$$b = 0.38 + 0.08\left(\frac{S}{S_0}\right) \tag{39b}$$

2.1.5. Model 5: Dogniaux and Lemoine model

Dogniaux and Lemoine proposed the following correlation, where the regression coefficients of the Angström–Prescott model [4] seem to be as a function of the latitude of the site [36]:

$$\frac{H}{H_0} = 0.37022 + \left[0.00506\left(\frac{S}{S_0}\right) - 0.00313\right]\varphi + 0.32029\left(\frac{S}{S_0}\right) \tag{40}$$

They also in same year obtained the specific monthly correlations which are listed in Eq (41a)–(41l) [36]:

January $$\frac{H}{H_0} = (-0.00301\varphi + 0.34507) + (0.00495\varphi + 0.34572)\left(\frac{S}{S_0}\right) \tag{41a}$$

February $$\frac{H}{H_0} = (-0.00255\varphi + 0.33459) + (0.00457\varphi + 0.35533)\left(\frac{S}{S_0}\right) \tag{41b}$$

March $$\frac{H}{H_0} = (-0.00303\varphi + 0.36690) + (0.00466\varphi + 0.36377)\left(\frac{S}{S_0}\right) \tag{41c}$$

April $$\frac{H}{H_0} = (-0.00334\varphi + 0.38557) + (0.00456\varphi + 0.35802)\left(\frac{S}{S_0}\right) \tag{41d}$$

May $$\frac{H}{H_0} = (-0.00245\varphi + 0.35057) + (0.00485\varphi + 0.33550)\left(\frac{S}{S_0}\right) \tag{41e}$$

June $$\frac{H}{H_0} = (-0.00327\varphi + 0.39890) + (0.00578\varphi + 0.27292)\left(\frac{S}{S_0}\right) \tag{41f}$$

July $$\frac{H}{H_0} = (-0.00369\varphi + 0.41234) + (0.00568\varphi + 0.27004)\left(\frac{S}{S_0}\right) \tag{41g}$$

August $$\frac{H}{H_0} = (-0.00269\varphi + 0.36243) + (0.00412\varphi + 0.33162)\left(\frac{S}{S_0}\right) \tag{41h}$$

September $$\frac{H}{H_0} = (-0.00338\varphi + 0.39467) + (0.00564\varphi + 0.27125)\left(\frac{S}{S_0}\right) \tag{41i}$$

October $$\frac{H}{H_0} = (-0.00317\varphi + 0.36213) + (0.00504\varphi + 0.31790)\left(\frac{S}{S_0}\right) \tag{41j}$$

November $$\frac{H}{H_0} = (-0.00350\varphi + 0.36680) + (0.00523\varphi + 0.31467)\left(\frac{S}{S_0}\right) \tag{41k}$$

December $$\frac{H}{H_0} = (-0.00350\varphi + 0.36262) + (0.00559\varphi + 0.30675)\left(\frac{S}{S_0}\right) \tag{41l}$$

2.1.6. Model 6: Kilic and Ozturk model

Kilic and Ozturk calculated the a and b regression coefficients of Angström model [4] for Turkey [37]:

$$a = 0.103 + 0.000017\,Z + 0.198cos(\varphi - \delta) \tag{42a}$$

$$b = 0.533 - 0.165\,cos(\varphi - \delta) \tag{42b}$$

2.1.7. Model 7: Benson et al. model

Benson et al. proposed two different formulations for two intervals of a year depending on the climatic parameters to estimate the global solar radiation [38]:

For January–March and October–December

$$\frac{H}{H_0}=0.18+0.6\left(\frac{S}{S_0}\right) \tag{43a}$$

For April–September

$$\frac{H}{H_0}=0.24+0.53\left(\frac{S}{S_0}\right) \tag{43b}$$

2.1.8. Model 8: Ogelman et al. model

Ogelman et al. expressed the ratio of global to extraterrestrial radiation by a second order polynomial function of the ratio of sunshine duration [39]:

$$\frac{H}{H_0}=a+b\left(\frac{S}{S_0}\right)+c\left(\frac{S}{S_0}\right)^2 \tag{44a}$$

$$\frac{H}{H_0}=0.195+0.676\left(\frac{S}{S_0}\right)-0.142\left(\frac{S}{S_0}\right)^2 \tag{44b}$$

Many authors in all over the world applied this model and determined the regression coefficient of this model for particular location of interest as follows:

- Akinoglu and Ecevit model for Turkey [40]

$$\frac{H}{H_0}=0.145+0.845\left(\frac{S}{S_0}\right)-0.280\left(\frac{S}{S_0}\right)^2 \tag{45}$$

- Almorox and Hontoria model for Spain [13]

$$\frac{H}{H_0}=0.1840+0.6792\left(\frac{S}{S_0}\right)-0.1228\left(\frac{S}{S_0}\right)^2 \tag{46}$$

- Bakirci model for Turkey [8]

$$\frac{H}{H_0}=0.2545+0.5121\left(\frac{S}{S_0}\right)-0.0864\left(\frac{S}{S_0}\right)^2 \tag{47}$$

- Tasdemiroglu and Sever model for Ankara, Antalya, Diyarbakir, Gebze, Izmir and Samsun in Turkey [41]

$$\frac{H}{H_0}=0.225+0.014\left(\frac{S}{S_0}\right)+0.001\left(\frac{S}{S_0}\right)^2 \tag{48}$$

- Yildiz and Oz model for Turkey [42]

$$\frac{H}{H_0}=0.2038+0.9236\left(\frac{S}{S_0}\right)-0.3911\left(\frac{S}{S_0}\right)^2 \tag{49}$$

- Aksoy model for Ankara, Antalya, Samsun, Konya, Urfa and Izmir, Turkey [43]

$$\frac{H}{H_0}=0.148+0.668\left(\frac{S}{S_0}\right)-0.079\left(\frac{S}{S_0}\right)^2 \tag{50}$$

- Said et al. model for Tripoli, Libya [17]

$$\frac{H}{H_0}=0.1+0.874\left(\frac{S}{S_0}\right)-0.255\left(\frac{S}{S_0}\right)^2 \tag{51}$$

- Ulgen and Ozbalta model for Izmir-Bornova, Turkey [18]

$$\frac{H}{H_0}=0.0959+0.9958\left(\frac{S}{S_0}\right)-0.3922\left(\frac{S}{S_0}\right)^2 \tag{52}$$

- Togrul and Togrul model for Ankara, Antalya, Izmir, Yenihisar (Aydin), Yumurtalik (Adana) and Elazig in Turkey [26]

$$\frac{H}{H_0}=0.1541+1.1714\left(\frac{S}{S_0}\right)-0.705\left(\frac{S}{S_0}\right)^2 \tag{53}$$

- Ahmad and Ulfat model for Karachi, Pakistan [21]

$$\frac{H}{H_0}=0.348+0.320\left(\frac{S}{S_0}\right)+0.070\left(\frac{S}{S_0}\right)^2 \tag{54}$$

- Tahran and Sari model for Central Black Sea Region of Turkey [44]

$$\frac{H}{H_0}=0.1874+0.8592\left(\frac{S}{S_0}\right)-0.4764\left(\frac{S}{S_0}\right)^2 \tag{55}$$

- Jin et al. model for 69 stations in China [22]

$$\frac{H}{H_0}=0.1404+0.6126\left(\frac{S}{S_0}\right)+0.0351\left(\frac{S}{S_0}\right)^2 \tag{56}$$

- Aras et al. model for twelve provinces in the Central Anatolia Region of Turkey [25]

$$\frac{H}{H_0}=0.3398+0.2868\left(\frac{S}{S_0}\right)+0.1187\left(\frac{S}{S_0}\right)^2 \tag{57}$$

- Ampratwum and Dorvlo model for Seeb and Sallalah weather stations in Oman, respectively [31]

$$\frac{H}{H_0}=0.9428-1.2027\left(\frac{S}{S_0}\right)+0.9336\left(\frac{S}{S_0}\right)^2 \tag{58a}$$

$$\frac{H}{H_0}=0.1971+0.6297\left(\frac{S}{S_0}\right)-0.2637\left(\frac{S}{S_0}\right)^2 \tag{58b}$$

2.1.9. Model 9: Bahel et al. model

Bahel et al. reported the following relationship [45]:

$$\frac{H}{H_0}=0.175+0.552\left(\frac{S}{S_0}\right) \tag{59}$$

2.1.10. Model 10: Zabara model

Zabara correlated monthly a and b values of the Angström–Prescott model [4] with monthly relative sunshine duration (S/S_0) as a third order function and expressed the a and b coefficients as [46]:

$$a=0.395-1.247\left(\frac{S}{S_0}\right)+2.680\left(\frac{S}{S_0}\right)^2-1.674\left(\frac{S}{S_0}\right)^3 \tag{60a}$$

$$b=0.395+1.384\left(\frac{S}{S_0}\right)-3.249\left(\frac{S}{S_0}\right)^2+2.055\left(\frac{S}{S_0}\right)^3 \tag{60b}$$

2.1.11. Model 11: Bahel model

Bahel developed a worldwide correlation based on bright sunshine hours and global radiation data of 48 stations around the world, with varied meteorological conditions and a wide distribution of geographic locations [47].

$$\frac{H}{H_0}=0.16+0.87\left(\frac{S}{S_0}\right)-0.61\left(\frac{S}{S_0}\right)^2+0.34\left(\frac{S}{S_0}\right)^3 \tag{61}$$

2.1.12. Model 12: Gopinathan model

Gopinathan suggested a and b regression coefficients of Angström–Prescott model [4] as a function of elevation (Z) and sunshine ratio (S/S_0) for estimation of the global solar radiation [48]:

$$a = 0.265 + 0.07Z - 0.135\left(\frac{S}{S_0}\right) \quad (62a)$$

$$b = 0.401 - 0.108Z + 0.325\left(\frac{S}{S_0}\right) \quad (62b)$$

Gopinathan also reported the following correlations [49]:

$$\frac{H}{H_0} = \left[-0.309 + 0.539\,cos\varphi - 0.0693Z + 0.290\left(\frac{S}{S_0}\right)\right] + \left[1.527 - 1.027\,cos\varphi + 0.0926Z - 0.359\left(\frac{S}{S_0}\right)\right]\left(\frac{S}{S_0}\right) \quad (63)$$

2.1.13. Model 13: Newland model

A linear-logarithmic model, has been used by Newland to obtain the best correlation between $H/H_0$and S/S_0 [50]:

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) + clog\left(\frac{S}{S_0}\right) \quad (64a)$$

$$\frac{H}{H_0} = 0.34 + 0.40\left(\frac{S}{S_0}\right) + 0.17log\left(\frac{S}{S_0}\right) \quad (64b)$$

Some applications of this model are:

– Bakirci model for Turkey [8]

$$\frac{H}{H_0} = 0.3925 + 0.2877\left(\frac{S}{S_0}\right) + 0.1527\,log\left(\frac{S}{S_0}\right) \quad (65)$$

– Ampratwum and Dorvlo model for Seeb and Sallalah weather stations in Oman, respectively [31]

$$\frac{H}{H_0} = -1.1931 + 1.8641\left(\frac{S}{S_0}\right) - 1.2544\,log\left(\frac{S}{S_0}\right) \quad (66a)$$

$$\frac{H}{H_0} = 0.4337 + 0.1430\left(\frac{S}{S_0}\right) + 0.0861\,log\left(\frac{S}{S_0}\right) \quad (66b)$$

2.1.14. Model 14: Monthly specific Rietveld model (Soler model)

Soler applied Rietveld's model to 100 European stations and gave the following specific monthly correlations [51]:

January $$\frac{H}{H_0} = 0.18 + 0.66\left(\frac{S}{S_0}\right) \quad (67a)$$

February $$\frac{H}{H_0} = 0.20 + 0.60\left(\frac{S}{S_0}\right) \quad (67b)$$

March $$\frac{H}{H_0} = 0.22 + 0.58\left(\frac{S}{S_0}\right) \quad (67c)$$

April $$\frac{H}{H_0} = 0.20 + 0.62\left(\frac{S}{S_0}\right) \quad (67d)$$

May $$\frac{H}{H_0} = 0.24 + 0.52\left(\frac{S}{S_0}\right) \quad (67e)$$

June $$\frac{H}{H_0} = 0.24 + 0.53\left(\frac{S}{S_0}\right) \quad (67f)$$

July $$\frac{H}{H_0} = 0.23 + 0.53\left(\frac{S}{S_0}\right) \quad (67g)$$

August $$\frac{H}{H_0} = 0.22 + 0.55\left(\frac{S}{S_0}\right) \quad (67h)$$

September $$\frac{H}{H_0} = 0.20 + 0.59\left(\frac{S}{S_0}\right) \quad (67i)$$

October $$\frac{H}{H_0} = 0.19 + 0.60\left(\frac{S}{S_0}\right) \quad (67j)$$

November $$\frac{H}{H_0} = 0.17 + 0.66\left(\frac{S}{S_0}\right) \quad (67k)$$

December $$\frac{H}{H_0} = 0.18 + 0.65\left(\frac{S}{S_0}\right) \quad (67l)$$

Also, they reported the regression coefficients of a and b as follows [51]:

$$a = 0.179 + 0.099\left(\frac{S}{S_0}\right) \quad (68a)$$

$$b = 0.1640 + 0.1786\left(\frac{S}{S_0}\right) - 1.0935\left(\frac{S}{S_0}\right)^2 \quad (68b)$$

2.1.15. Model 15: Luhanga and Andringa model

Luhanga and Andringa derived their own model as follow [52]:

$$\frac{H}{H_0} = 0.241 + 0.488\left(\frac{S}{S_0}\right) \quad (69)$$

2.1.16. Model 16: Louche et al. model

Louche et al. presented the model below to predict global solar radiation [53]:

$$\frac{H}{H_0} = 0.206 + 0.546\left(\frac{S}{S_0}\right) \quad (70)$$

Furthermore, the Angström–Prescott model [4] has been modified through the use of the ratio of (S/S_{nh})instead of (S/S_0) by Louche et al. model which is presented as follows [53]:

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_{nh}}\right) \quad (71a)$$

$$\frac{1}{S_{nh}} = \frac{0.8706}{S_0} + 0.0003 \quad (71b)$$

2.1.17. Model 17: Samuel model

Samuel has correlated $H/H_0$with S/S_0 in the form of a third order polynomial equation [54]:

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) + c\left(\frac{S}{S_0}\right)^2 + d\left(\frac{S}{S_0}\right)^3 \quad (72a)$$

$$\frac{H}{H_0} = -0.14 + 2.52\left(\frac{S}{S_0}\right) - 3.71\left(\frac{S}{S_0}\right)^2 + 2.24\left(\frac{S}{S_0}\right)^3 \quad (72b)$$

Some investigator used this model to estimate global solar radiation in different locations all over the world. Some of these models are:

– Ertekin and yaldiz model for Antalya, Turkey [55]

$$\frac{H}{H_0} = -2.4275 + 11.946\left(\frac{S}{S_0}\right) - 16.745\left(\frac{S}{S_0}\right)^2 + 7.9575\left(\frac{S}{S_0}\right)^3 \quad (73)$$

– Almorox and Hontoria model for Spain [13]

$$\frac{H}{H_0}=0.230+0.3809\left(\frac{S}{S_0}\right)+0.4694\left(\frac{S}{S_0}\right)^2-0.3657\left(\frac{S}{S_0}\right)^3 \quad (74)$$

– Lewis model for state of Tennessee, U.S.A. [11]

$$\frac{H}{H_0}=0.81-3.34\left(\frac{S}{S_0}\right)+7.38\left(\frac{S}{S_0}\right)^2-4.51\left(\frac{S}{S_0}\right)^3 \quad (75)$$

– Ulgen and Hepbasli model for Izmir, Turkey [33]

$$\frac{H}{H_0}=0.2408+0.3625\left(\frac{S}{S_0}\right)+0.4597\left(\frac{S}{S_0}\right)^2-0.3708\left(\frac{S}{S_0}\right)^3 \quad (76)$$

– Togrul and Togrul model for Ankara, Antalya, Izmir, Yenihisar (Aydin), Yumurtalik (Adana) and Elazig in Turkey [26]

$$\frac{H}{H_0}=0.1796+0.9813\left(\frac{S}{S_0}\right)-0.2958\left(\frac{S}{S_0}\right)^2-0.2657\left(\frac{S}{S_0}\right)^3 \quad (77)$$

– Ulgen and Hepbasli model for Ankara, Istanbul and Izmir in Turkey [24]

$$\frac{H}{H_0}=0.2854+0.2591\left(\frac{S}{S_0}\right)+0.6171\left(\frac{S}{S_0}\right)^2-0.4834\left(\frac{S}{S_0}\right)^3 \quad (78)$$

– Tahran and Sari model for Central Black Sea Region of Turkey [44]

$$\frac{H}{H_0}=0.1520+1.1334\left(\frac{S}{S_0}\right)-1.1126\left(\frac{S}{S_0}\right)^2+0.4516\left(\frac{S}{S_0}\right)^3 \quad (79)$$

– Jin et al. model for 69 stations in China [22]

$$\frac{H}{H_0}=0.1275+0.7251\left(\frac{S}{S_0}\right)-0.2299\left(\frac{S}{S_0}\right)^2+0.1837\left(\frac{S}{S_0}\right)^3 \quad (80)$$

– Aras et al. model for twelve provinces in the Central Anatolia Region of Turkey [25]

$$\frac{H}{H_0}=0.4832-0.6161\left(\frac{S}{S_0}\right)+1.8932\left(\frac{S}{S_0}\right)^2-1.0975\left(\frac{S}{S_0}\right)^3 \quad (81)$$

– Rensheng et al. model for 86 stations in China [20]

$$\frac{H}{H_0}=0.150+1.145\left(\frac{S}{S_0}\right)-1.474\left(\frac{S}{S_0}\right)^2+0.963\left(\frac{S}{S_0}\right)^3 \quad (82)$$

– Bakirci Model for Erzurum, Turkey [56]

$$\frac{H}{H_0}=0.6307-0.7251\left(\frac{S}{S_0}\right)+1.2089\left(\frac{S}{S_0}\right)^2-0.4633\left(\frac{S}{S_0}\right) \quad (83)$$

2.1.18. Model 18: Gopinathan and Soler model

Gopinathan and Soler suggested following linear equations for locations with latitudes between 60°N and 70°N [57]:

$$\frac{H}{H_0}=0.1538+0.7874\left(\frac{S}{S_0}\right) \quad (84a)$$

$$\frac{H}{H_0}=0.1961+0.7212\left(\frac{S}{S_0}\right) \quad (84b)$$

2.1.19. Model 19: Raja model

Based on Bennett's formula [58], Raja proposed the following insolation-sunshine relation [59]:

$$\frac{H}{H_0}=\left[0.368-0.125\left(1-\frac{Z}{Z_a}\right)\right]+\left[0.667-0.018\left(1-\frac{Z}{Z_a}\right)-0.211\ cos\varphi\right]\frac{S}{S_{04}} \quad (85a)$$

where $Z_a=8000\ m$ and S_{04} is the 4° corrected day length used to compensate the finite threshold of the Champbell–Stokes sunshine recorder and is calculated as follows:

$$S_{04}=\frac{2}{15}cos^{-1}\left[\frac{(sin4^\circ-sin\varphi sin\delta)}{cos\delta cos\varphi}\right] \quad (85b)$$

2.1.20. Model 20: Coppolino model

Coppolino developed a power function and incorporated a trigonometric term to estimate global solar radiation [60]:

(a) Power model

$$\frac{H}{H_0}=e^a\left(\frac{S}{S_0}\right)^b \quad (86)$$

– Ampratwum and Dorvlo model for Seeb and Sallalah weather stations in Oman, respectively [31]

$$\frac{H}{H_0}=e^{-0.4470}\left(\frac{S}{S_0}\right)^{0.4253} \quad (87a)$$

$$\frac{H}{H_0}=e^{-0.5561}\left(\frac{S}{S_0}\right)^{0.3588} \quad (87b)$$

(b) Power-trigonometric model

$$\frac{H}{H_0}=e^a\left(\frac{S}{S_0}\right)^b(sinh_\alpha)^c \quad (88)$$

The noon solar altitude angle of the Sun (h_α) is the complement of zenith angle and can be calculated from [60]:

$$h_\alpha=90-\varphi+\delta \quad (89)$$

– Coppolino employed this model to estimate global solar radiation in 34 Italian stations. The regression coefficients of this model are presented as follows [60]

$$\frac{H}{H_0}=0.67\left(\frac{S}{S_0}\right)^{0.45}(sinh_\alpha)^{0.05} \quad 0.15\le\left(\frac{S}{S_0}\right)\le0.90 \quad (90)$$

– Ampratwum and Dorvlo model for Seeb and Sallalah weather stations in Oman, respectively [31]

$$\frac{H}{H_0}=e^{-0.4135}\left(\frac{S}{S_0}\right)^{0.5239}(sinh_\alpha)^{0.0911} \quad (91a)$$

$$\frac{H}{H_0}=e^{-0.5598}\left(\frac{S}{S_0}\right)^{0.3571}(sinh_\alpha)^{-0.0296} \quad (91b)$$

2.1.21. Model 21: Tiris et al. model

Tiris et al. reported their own correlations as follow [61]:

$$\frac{H}{H_0}=0.2262+0.418\left(\frac{S}{S_0}\right) \quad (92)$$

2.1.22. Model 22: Ampratwum and Dorvlo model

Ampratwum and Dorvlo have suggested a logarithmic type model as [31]:

$$\frac{H}{H_0}=a+b\ log\left(\frac{S}{S_0}\right) \quad (93)$$

Some other developed logarithmic correlations are:

– Almorox and Hontoria model for Spain [13]

$$\frac{H}{H_0} = 0.6902 + 0.6142\,log\left(\frac{S}{S_0}\right) \quad (94)$$

– Ampratwum and Dorvlo model for Seeb and Sallalah weather stations in Oman, respectively [31]

$$\frac{H}{H_0} = 0.6376 + 0.2490\,log\left(\frac{S}{S_0}\right) \quad (95a)$$

$$\frac{H}{H_0} = 0.5612 + 0.1412\,log\left(\frac{S}{S_0}\right) \quad (95b)$$

– Bakirci model for Turkey [8]

$$\frac{H}{H_0} = 0.6446 + 0.4842\,log\left(\frac{S}{S_0}\right) \quad (96)$$

– Togrul and Togrul model for Ankara, Antalya, Izmir, Yenihisar (Aydin), Yumurtalik (Adana) and Elazig in Turkey [26]

$$\frac{H}{H_0} = 0.698 + 0.2022\,log\left(\frac{S}{S_0}\right) \quad (97)$$

2.1.23. Model 23: Klabzuba et al. model

Klabzuba et al. developed the following relationship between the measured H and the relative sunshine duration [62]:

$$H = a + b\left(\frac{S}{S_0}\right) + c\left[d + \left(\frac{S}{S_0}\right)\right](n-e)^2 \quad (98)$$

– Klabzuba et al. model for Hradec Králové solar observatory, Czech Republic [62]

$$H = 7.19 + 0.258\left(\frac{S}{S_0}\right) - 9.28\times10^{-6}\left[\left(\frac{S}{S_0}\right) + 22.9\right](n-174.7)^2 \quad (99)$$

2.1.24. Model 24: Togrul et al. model

Togrul et al. applied the various regression analyses to investigate the relation between monthly mean S/S_0 ratio and constants a and b in Angström model [4] as follow [63]:

$$a = i + j\left(\frac{S}{S_0}\right); \quad b = k + l\left(\frac{S}{S_0}\right) \quad (100a)$$

$$a = i\,ln\left(\frac{S}{S_0}\right) + j; \quad b = k\,ln\left(\frac{S}{S_0}\right) + m \quad (100b)$$

$$a = i + j\left(\frac{S}{S_0}\right) + k\left(\frac{S}{S_0}\right)^2; \quad b = l + m\left(\frac{S}{S_0}\right) + n\left(\frac{S}{S_0}\right)^2 \quad (100c)$$

$$a = i + j\left(\frac{S}{S_0}\right) + k\left(\frac{S}{S_0}\right)^2 + l\left(\frac{S}{S_0}\right)^3; \quad b = m + n\left(\frac{S}{S_0}\right) + p\left(\frac{S}{S_0}\right)^2 + r\left(\frac{S}{S_0}\right)^3 \quad (100d)$$

$$a = i + j\left(\frac{S}{S_0}\right) + k\left(\frac{S}{S_0}\right)^2 + l\left(\frac{S}{S_0}\right)^3 + m\left(\frac{S}{S_0}\right)^4$$
$$b = n + p\left(\frac{S}{S_0}\right) + r\left(\frac{S}{S_0}\right)^2 + t\left(\frac{S}{S_0}\right)^3 + v\left(\frac{S}{S_0}\right)^4 \quad (100e)$$

– Togrul et al. obtained the empirical coefficients of their models for Elazig, Turkey as follows [63]

$$a = 0.2816 - 0.1049\left(\frac{S}{S_0}\right); \quad b = 0.4762 - 0.0174\left(\frac{S}{S_0}\right) \quad (101a)$$

$$a = -0.0344ln\left(\frac{S}{S_0}\right) + 0.1982; \quad b = -0.0201ln\left(\frac{S}{S_0}\right) + 0.4562 \quad (101b)$$

$$a = 0.1950 + 0.2943\left(\frac{S}{S_0}\right) - 0.3706\left(\frac{S}{S_0}\right)^2$$
$$b = 0.6248 - 0.7033\left(\frac{S}{S_0}\right) + 0.6368\left(\frac{S}{S_0}\right)^2 \quad (101c)$$

$$a = 0.2646 - 0.2958\left(\frac{S}{S_0}\right) + 0.9671\left(\frac{S}{S_0}\right)^2 - 0.8749\left(\frac{S}{S_0}\right)^3$$
$$b = 0.5403 + 0.0149\left(\frac{S}{S_0}\right) - 0.9913\left(\frac{S}{S_0}\right)^2 + 1.0649\left(\frac{S}{S_0}\right)^3 \quad (101d)$$

$$a = 0.2226 + 0.2841\left(\frac{S}{S_0}\right) - 1.3653\left(\frac{S}{S_0}\right)^2 + 2.6661\left(\frac{S}{S_0}\right)^3 - 1.7997\left(\frac{S}{S_0}\right)^4$$
$$b = 0.561 - 0.2715\left(\frac{S}{S_0}\right) + 0.1606\left(\frac{S}{S_0}\right)^2 - 0.6839\left(\frac{S}{S_0}\right)^3 + 0.8888\left(\frac{S}{S_0}\right)^4 \quad (101e)$$

2.1.25. Model 25: Elagib and Mansell model

Elagib and Mansell developed new techniques for predicting solar radiation based on sunshine hours and geographical parameters [64]:

$$\frac{H}{H_0} = a\,exp\left[b\left(\frac{S}{S_0}\right)\right] \quad (102a)$$

$$\frac{H}{H_0} = a + bL + cZ + d\left(\frac{S}{S_0}\right) \quad (102b)$$

$$\frac{H}{H_0} = a + bL + c\left(\frac{S}{S_0}\right) \quad (102c)$$

$$\frac{H}{H_0} = a + bZ + c\left(\frac{S}{S_0}\right) \quad (102d)$$

Some researchers calibrated the Elagib and Mansell models for different locations. Some of these models are as follows:

– Togrul and Togrul model for Ankara, Antalya, Izmir, Yenihisar (Aydin), Yumurtalik (Adana) and Elazig in Turkey [26]

$$\frac{H}{H_0} = 0.3396\,exp\left[0.8985\left(\frac{S}{S_0}\right)\right] \quad (103)$$

– Jin et al. model for 69 stations in China [22]

$$\frac{H}{H_0} = 0.0855 + 0.002L + 0.03Z + 0.5654\left(\frac{S}{S_0}\right) \quad (104)$$

– Rensheng et al. model for 86 stations in China [20]

$$\frac{H}{H_0} = 0.122 + 0.001L + 2.57\times10^{-2}Z + 0.543\left(\frac{S}{S_0}\right) \quad (105)$$

2.1.26. Model 26: Monthly specific Elagib and Mansell model

Elagib and Mansell have investigated the possibility of establishing monthly-specific equations for estimating global solar radiation across Sudan. The best performing equations for each month are given as following [64]:

January $$\frac{H}{H_0}=0.1357+0.3204L+0.0422Z+0.4947\left(\frac{S}{S_0}\right) \quad (106a)$$

February $$\frac{H}{H_0}=0.1563+0.3166L+0.1006Z+0.4593\left(\frac{S}{S_0}\right) \quad (106b)$$

March $$\frac{H}{H_0}=0.7727\left(\frac{S}{S_0}\right)^{0.7263} \quad (106c)$$

April $$\frac{H}{H_0}=0.1640+0.0397Z+0.5773\left(\frac{S}{S_0}\right) \quad (106d)$$

May $$\frac{H}{H_0}=0.0709+0.8967\left(\frac{S}{S_0}\right)-0.2258\left(\frac{S}{S_0}\right)^2 \quad (106e)$$

June $$\frac{H}{H_0}=-0.0348+1.5078\left(\frac{S}{S_0}\right)-0.8246\left(\frac{S}{S_0}\right)^2 \quad (106f)$$

July $$\frac{H}{H_0}=0.3205+0.1444L+0.0782Z+0.2916\left(\frac{S}{S_0}\right) \quad (106g)$$

August $$\frac{H}{H_0}=0.2720+0.0369L+0.1017Z+0.3888\left(\frac{S}{S_0}\right) \quad (106h)$$

September $$\frac{H}{H_0}=-0.3710+2.5783\left(\frac{S}{S_0}\right)-1.6788\left(\frac{S}{S_0}\right)^2 \quad (106i)$$

October $$\frac{H}{H_0}=0.1593-0.1043L+0.0609Z+0.5916\left(\frac{S}{S_0}\right) \quad (106j)$$

November $$\frac{H}{H_0}=0.1786+0.0199Z+0.5441\left(\frac{S}{S_0}\right) \quad (106k)$$

December $$\frac{H}{H_0}=0.1714+0.1329L+0.0482Z+0.5015\left(\frac{S}{S_0}\right) \quad (106l)$$

2.1.27. Model 27: Togrul et al. model

Togrul et al. developed some statistical relations to estimate monthly mean daily global solar radiation by using clear sky radiation. The correlations have been developed by employing both ratios of (S/S_0) and (S/S_{nh})[65].

where S_{nh} is the monthly mean sunshine duration that take into account the natural horizon of the site and can be calculated by following equation:

$$\frac{1}{S_{nh}}=\frac{0.8706}{S_0}+0.0003 \quad (107)$$

For summer

$$\frac{H}{H_c}=0.5771+0.6843\left(\frac{S}{S_0}\right)-0.3544\left(\frac{S}{S_0}\right)^2 \quad (108a)$$

$$\frac{H}{H_c}=0.4356+1.3939\left(\frac{S}{S_0}\right)-1.4988\left(\frac{S}{S_0}\right)^2+0.5954\left(\frac{S}{S_0}\right)^3 \quad (108b)$$

$$\frac{H}{H_c}=0.7295exp\left[0.2633\left(\frac{S}{S_0}\right)\right] \quad (108c)$$

$$\frac{H}{H_c}=0.9337\left(\frac{S}{S_0}\right)^{0.1688} \quad (108d)$$

$$\frac{H}{H_c}=0.577+0.7825\left(\frac{S}{S_{nh}}\right)-0.4631\left(\frac{S}{S_{nh}}\right)^2 \quad (108e)$$

$$\frac{H}{H_c}=0.4356+1.5935\left(\frac{S}{S_{nh}}\right)-1.9584\left(\frac{S}{S_{nh}}\right)^2+0.8893\left(\frac{S}{S_{nh}}\right)^3 \quad (108f)$$

$$\frac{H}{H_c}=0.9552\left(\frac{S}{S_{nh}}\right)^{0.1689} \quad (108g)$$

For winter

$$\frac{H}{H_c}=0.2384+2.1498\left(\frac{S}{S_0}\right)-1.8664\left(\frac{S}{S_0}\right)^2 \quad (109a)$$

$$\frac{H}{H_c}=0.3081+1.4933\left(\frac{S}{S_0}\right)-0.0839\left(\frac{S}{S_0}\right)^2-1.4513\left(\frac{S}{S_0}\right)^3 \quad (109b)$$

$$\frac{H}{H_c}=0.5451\ exp\left[0.7981\left(\frac{S}{S_0}\right)\right] \quad (109c)$$

$$\frac{H}{H_c}=1.0302\left(\frac{S}{S_0}\right)^{0.3204} \quad (109d)$$

$$\frac{H}{H_c}=0.2385+2.4604\left(\frac{S}{S_{nh}}\right)-2.445\left(\frac{S}{S_{nh}}\right)^2 \quad (109e)$$

$$\frac{H}{H_c}=0.3077+1.7137\left(\frac{S}{S_{nh}}\right)-0.1251\left(\frac{S}{S_{nh}}\right)^2-2.1612\left(\frac{S}{S_{nh}}\right)^3 \quad (109f)$$

$$\frac{H}{H_c}=1.0755\left(\frac{S}{S_{nh}}\right)^{0.3202} \quad (109g)$$

2.1.28. Model 28: Almorox and Hontoria model

Almorox and Hontoria proposed the following exponential correlation to estimate global solar radiation from sunshine hours [13]:

$$\frac{H}{H_0}=a+b\ exp\left(\frac{S}{S_0}\right) \quad (110)$$

– Almorox and Hontoria model for Spain [13]

$$\frac{H}{H_0}=-0.0271+0.3096\ exp\left(\frac{S}{S_0}\right) \quad (111)$$

– Bakirci model for Turkey [8]

$$\frac{H}{H_0}=0.0963+0.2337\ exp\left(\frac{S}{S_0}\right) \quad (112)$$

2.1.29. Model 29: Jin et al. model

Jin et al. proposed the following models by using solar radiation data and some geographical parameters like latitude and altitude [22]:

$$\frac{H}{H_0}=a+bcos\varphi+cZ+d\left(\frac{S}{S_0}\right) \quad (113a)$$

$$\frac{H}{H_0}=(a+bL+cZ)+(d+eL+fZ)\left(\frac{S}{S_0}\right) \quad (113b)$$

$$\frac{H}{H_0}=(a+bcos\varphi+cZ)+(d+ecos\varphi+fZ)\left(\frac{S}{S_0}\right) \quad (113c)$$

$$\frac{H}{H_0}=(a+bL+cZ)+(d+eL+fZ)\left(\frac{S}{S_0}\right)+(g+hL+iZ)\left(\frac{S}{S_0}\right)^2 \quad (113d)$$

$$\frac{H}{H_0}=(a+bcos\varphi+cZ)+(d+ecos\varphi+fZ)\left(\frac{S}{S_0}\right)$$

$$+\left(g+h\cos\varphi+iZ\right)\left(\frac{S}{S_0}\right)^2 \tag{113e}$$

Some implications of these models are:

– Jin et al. model for 69 stations in China [22]

$$\frac{H}{H_0}=2.1186-2.0014\cos\varphi+0.0304Z+0.5622\left(\frac{S}{S_0}\right) \tag{114a}$$

$$\frac{H}{H_0}=(0.1094+0.0014L+0.0212Z)+(0.5176+0.0012L+0.0150Z)\left(\frac{S}{S_0}\right) \tag{114b}$$

$$\frac{H}{H_0}=\left(1.8790-1.7516\cos\varphi+0.0205Z\right)+\left(1.0819-0.5409\cos\varphi+0.0169Z\right)\left(\frac{S}{S_0}\right) \tag{114c}$$

$$\frac{H}{H_0}=(0.0218+0.0033L+0.0443Z)+(0.9979-0.0092L-0.0852Z)\left(\frac{S}{S_0}\right)+\left(-0.5579+0.0120\varphi+0.1005Z\right)\left(\frac{S}{S_0}\right)^2 \tag{114d}$$

$$\frac{H}{H_0}=\left(4.2510-4.1878\cos\varphi+0.0437Z\right)+\left(-10.5774+11.4512\cos\varphi-0.0832Z\right)\left(\frac{S}{S_0}\right) \tag{114e}$$

– Rensheng et al. model for 86 stations in China [20]

$$\frac{H}{H_0}=0.280-0.141\cos\varphi+2.60\times10^{-2}Z+0.542\left(\frac{S}{S_0}\right) \tag{115a}$$

$$\frac{H}{H_0}=\left(0.329-0.196\cos\varphi+2.2\times10^{-2}Z\right)+\left(0.457+0.097\cos\varphi+6.72\times10^{-3}Z\right)\left(\frac{S}{S_0}\right) \tag{115b}$$

2.1.30. Model 30: El-Metwally model

El-Metwally proposed a non-linear correlation between clear index (H/H_0) and relative sunshine (S/S_0) as follows [7]:

$$\frac{H}{H_0}=a^{(1/S/S_0)} \tag{116}$$

– El-Metwally model for Egypt [7]

$$\frac{H}{H_0}=0.713^{(1/S/S_0)} \tag{117}$$

2.1.31. Model 31: Almorox et al. model

Almorox et al. reported the monthly-specific equations for estimating global solar radiation from sunshine hours for Toledo, Spain as given by following correlations [66]:

$$\text{January}\quad \frac{H}{H_0}=0.285+0.444\left(\frac{S}{S_0}\right) \tag{118a}$$

$$\text{February}\quad \frac{H}{H_0}=0.272+0.465\left(\frac{S}{S_0}\right) \tag{118b}$$

$$\text{March}\quad \frac{H}{H_0}=0.291+0.491\left(\frac{S}{S_0}\right) \tag{118c}$$

$$\text{April}\quad \frac{H}{H_0}=0.266+0.495\left(\frac{S}{S_0}\right) \tag{118d}$$

$$\text{May}\quad \frac{H}{H_0}=0.286+0.475\left(\frac{S}{S_0}\right) \tag{118e}$$

$$\text{June}\quad \frac{H}{H_0}=0.311+0.439\left(\frac{S}{S_0}\right) \tag{118f}$$

$$\text{July}\quad \frac{H}{H_0}=0.329+0.406\left(\frac{S}{S_0}\right) \tag{118g}$$

$$\text{August}\quad \frac{H}{H_0}=0.313+0.410\left(\frac{S}{S_0}\right) \tag{118h}$$

$$\text{September}\quad \frac{H}{H_0}=0.271+0.479\left(\frac{S}{S_0}\right) \tag{118i}$$

$$\text{October}\quad \frac{H}{H_0}=0.259+0.465\left(\frac{S}{S_0}\right) \tag{118j}$$

$$\text{November}\quad \frac{H}{H_0}=0.279+0.431\left(\frac{S}{S_0}\right) \tag{118k}$$

$$\text{December}\quad \frac{H}{H_0}=0.282+0.428\left(\frac{S}{S_0}\right) \tag{118l}$$

2.1.32. Model 32: Rensheng et al. model

Rensheng et al. have suggested new equations, based on the Angström model [4] to estimate global radiation. These equations are as follows [20]:

$$\frac{H}{H_0}=(a+bL+cZ)+d\left(\frac{S}{S_0}\right)+e\left(\frac{S}{S_0}\right)^2+f\left(\frac{S}{S_0}\right)^3 \tag{119a}$$

$$\frac{H}{H_0}=\left(a+b\cos\varphi+cZ\right)+d\left(\frac{S}{S_0}\right)+e\left(\frac{S}{S_0}\right)^2+f\left(\frac{S}{S_0}\right)^3 \tag{119b}$$

$$\frac{H}{H_0}=\left(a+b\cos\varphi+cZ\right)+\left(d+e\cos\varphi+fZ\right)\left(\frac{S}{S_0}\right)+\left(g+h\cos\varphi+iZ\right)\left(\frac{S}{S_0}\right)^2+\left(j+k\cos\varphi+lZ\right)\left(\frac{S}{S_0}\right)^3 \tag{119c}$$

$$\frac{H}{H_0}=(a+bL+cZ+d\lambda)+e\left(\frac{S}{S_0}\right) \tag{119d}$$

$$\frac{H}{H_0}=\left(a+b\cos\varphi+cZ+d\lambda\right)+e\left(\frac{S}{S_0}\right) \tag{119e}$$

$$\frac{H}{H_0}=(a+bL+cZ+d\lambda)+(e+fL+gZ+h\lambda)\left(\frac{S}{S_0}\right) \tag{119f}$$

$$\frac{H}{H_0}=\left(a+b\cos\varphi+cZ+d\lambda\right)+\left(e+f\cos\varphi+gZ+h\lambda\right)\left(\frac{S}{S_0}\right) \tag{119g}$$

$$\frac{H}{H_0}=\left(a+bL+cZ+d\lambda+e\lambda^2\right)+f\left(\frac{S}{S_0}\right)+g\left(\frac{S}{S_0}\right)^2+h\left(\frac{S}{S_0}\right)^3 \tag{119h}$$

$$\frac{H}{H_0}=\left(a+b\cos\varphi+cZ+d\lambda+e\lambda^2\right)+f\left(\frac{S}{S_0}\right)+g\left(\frac{S}{S_0}\right)^2+h\left(\frac{S}{S_0}\right)^3 \tag{119i}$$

$$\frac{H}{H_0}=\left(a+b\cos\varphi+cZ+d\lambda+e\lambda^2\right)+\left(f+g\cos\varphi+hZ+i\lambda+j\lambda^2\right)\left(\frac{S}{S_0}\right)$$

$$+\left(k+l\cos\varphi+mZ+n\lambda+o\lambda^2\right)\left(\frac{S}{S_0}\right)^2$$
$$+\left(p+q\cos\varphi+rZ+s\lambda+t\lambda^2\right)\left(\frac{S}{S_0}\right)^3 \quad (119j)$$

- Rensheng et al. employed their models to obtain following correlations using data from 1994 to 1998 at 86 stations in China [20].

$$\frac{H}{H_0}=\left(0.109+0.001L+2.41\times10^{-2}Z\right)+1.029\left(\frac{S}{S_0}\right)-1.216\left(\frac{S}{S_0}\right)^2+0.787\left(\frac{S}{S_0}\right)^3 \quad (120a)$$

$$\frac{H}{H_0}=\left(0.234-0.112\cos\varphi+2.43\times10^{-2}Z\right)+1.026\left(\frac{S}{S_0}\right)-1.209\left(\frac{S}{S_0}\right)^2+0.782\left(\frac{S}{S_0}\right)^3 \quad (120b)$$

$$\frac{H}{H_0}=\left(0.336-0.233\cos\varphi+2.64\times10^{-2}Z\right)+(-0.670+2.140\cos\varphi-0.1Z)\left(\frac{S}{S_0}\right)+(2.744-5\cos\varphi+0.3Z)\left(\frac{S}{S_0}\right)^2+(-1.638+3.042\cos\varphi-0.2Z)\left(\frac{S}{S_0}\right)^3 \quad (120c)$$

$$\frac{H}{H_0}=\left(0.117-0.001L+2.59\times10^{-2}Z+4.11\times10^{-5}\lambda\right)+0.543\left(\frac{S}{S_0}\right) \quad (120d)$$

$$\frac{H}{H_0}=\left(0.275-0.141\cos\varphi+2.63\times10^{-2}Z+4.27\times10^{-5}\lambda\right)+0.542\left(\frac{S}{S_0}\right) \quad (120e)$$

$$\frac{H}{H_0}=\left(0.094+0.002L+2.27\times10^{-2}Z+0.0001\lambda\right)+\left(0.586-0.0008L+5.36\times10^{-3}Z-0.0002\lambda\right)\left(\frac{S}{S_0}\right) \quad (120f)$$

$$\frac{H}{H_0}=\left(0.313-0.195\cos\varphi+2.28\times10^{-2}Z+0.0001\lambda\right)+\left(0.476+0.097\cos\varphi+5.69\times10^{-3}Z-0.0002\lambda\right)\left(\frac{S}{S_0}\right) \quad (120g)$$

$$\frac{H}{H_0}=\left(0.370+0.0007L+2.44\times10^{-2}Z-0.005\lambda+2.24\times10^{-5}\lambda^2\right)+1.026\left(\frac{S}{S_0}\right)-1.208\left(\frac{S}{S_0}\right)^2+0.783\left(\frac{S}{S_0}\right)^3 \quad (120h)$$

$$\frac{H}{H_0}=\left(0.426-0.087\cos\varphi+2.44\times10^{-2}Z-0.004\lambda+1.86\times10^{-5}\lambda^2\right)+1.024\left(\frac{S}{S_0}\right)-1.204\left(\frac{S}{S_0}\right)^2+0.779\left(\frac{S}{S_0}\right)^3 \quad (120i)$$

$$\frac{H}{H_0}=\left(1.012-0.141\cos\varphi+2.84\times10^{-2}Z-0.014\lambda+6.7\times10^{-5}\lambda^2\right)+\left(-4.061+1.740\cos\varphi-0.1Z+0.069\lambda-0.003\lambda^2\right)\left(\frac{S}{S_0}\right)+\left(12.402-3.867\cos\varphi+0.3Z-0.199\lambda+0.0009\lambda^2\right)\left(\frac{S}{S_0}\right)^2+\left(-9.442+2.115\cos\varphi-0.2Z+0.164\lambda-0.0008\lambda^2\right)\left(\frac{S}{S_0}\right)^3 \quad (120j)$$

2.1.33. Model 33: Sen model

Sen proposed a nonlinear model for the estimation of global solar radiation from available sunshine duration data. This model is an Angström type model with a third parameter appears as the power of the sunshine duration ratio [67]:

$$\frac{H}{H_0}=a+b\left(\frac{S}{S_0}\right)^c \quad (121)$$

- El-Sebaii et al. calibrated this model For Jeddah, Saudi Arabia [19]

$$\frac{H}{H_0}=-0.864+1.862\left(\frac{S}{S_0}\right)^{2.344} \quad (122)$$

2.1.34. Model 34: Bakirci model

Bakirci reported the original Angström-type equations including the linear, second-order and fifth-order polynomial relationships between the monthly average values of (H/H_c) and (S/S_0) as follows [68]:

$$\frac{H}{H_c}=0.7836-0.0460\left(\frac{S}{S_0}\right) \quad (123a)$$

$$\frac{H}{H_c}=1.0192-1.0547\left(\frac{S}{S_0}\right)+0.9661\left(\frac{S}{S_0}\right)^2 \quad (123b)$$

$$\frac{H}{H_c}=-11.225+128.010\left(\frac{S}{S_0}\right)-516.900\left(\frac{S}{S_0}\right)^2+994.730\left(\frac{S}{S_0}\right)^3-920.350\left(\frac{S}{S_0}\right)^4+329.93\left(\frac{S}{S_0}\right)^5 \quad (123c)$$

2.1.35. Model 35: Bakirci model

Bakirci developed following models which is a derivation of the modified Angström-type equation [8]:

(a) Linear exponential

$$\frac{H}{H_0}=a+b\left(\frac{S}{S_0}\right)+c\exp\left(\frac{S}{S_0}\right) \quad (124)$$

Some other relations are:

- Muzathik et al. model for state of Terengganu, Malaysia [69]

$$\frac{H}{H_0}=0.19490+0.4771\left(\frac{S}{S_0}\right)+0.02994\exp\left(\frac{S}{S_0}\right) \quad (125)$$

- Bakirci model for Turkey [8]

$$\frac{H}{H_0}=0.3448+0.5636\left(\frac{S}{S_0}\right)-0.0838\exp\left(\frac{S}{S_0}\right) \quad (126)$$

(b) Exponent

$$\frac{H}{H_0}=a\left(\frac{S}{S_0}\right)^b \tag{127}$$

– Bakirci model for Turkey [8]

$$\frac{H}{H_0}=0.6660\left(\frac{S}{S_0}\right)^{0.4333} \tag{128}$$

– Togrul and Togrul model for Ankara, Antalya, Izmir, Yenihisar (Aydin), Yumurtalik (Adana) and Elazig in Turkey [26]

$$\frac{H}{H_0}=0.7316\left(\frac{S}{S_0}\right)^{0.4146} \tag{129}$$

2.2. Cloud-based models

Clouds and their accompanying weather patterns are among the most important atmospheric phenomena restricting the availability of solar radiation at the earth's surface. The cloudiness as a limiting factor causes distribution and dissipation of the solar radiation reaching the atmosphere and affects the amount of radiation received at the earth's surface. The cloud data are detected routinely by meteorological satellites, so a number of models have been developed to estimate global solar radiation from observations of various cloud layer amounts and cloud types [70]. In the following section, correlations which use only the cloudiness are presented and classified based on their developing year.

2.2.1. Model 1: Black model

Black developed following quadratic equation, using data from many parts of the world [71]:

$$\frac{H}{H_0}=0.803-0.340C-0.458C^2 \quad (C\le 0.8) \tag{130}$$

where C is mean total cloud cover during daytime observations in octa.

2.2.2. Model 2: Paltridge model

Paltridge and Proctor suggested a new model that is able to determine the instant and total daily radiation at any location of interest. This model takes the solar zenith angle (θ), day length (S_0) and cloud factor (CF) as inputs. Their model assumes that the effect of atmospheric water vapor, regional albedo and aerosol optical air mass on surface radiation is small (less than 5%) [72].

The hourly beam (I_b) and diffuse (I_d) radiation in (MJ/m^2 h) are determined by:

$$I_b=3.42286[1-exp(-0.075(90-\theta))] \tag{131a}$$

$$I_d=0.00913+0.0125(90-\theta)+0.723\mathrm{CF} \tag{131b}$$

The mean monthly Total daily global radiation on horizontal surface (MJ/m^2 day) were computed from correlations below:

$$H=H_b+H_d \tag{131c}$$

$$H=(1-\mathrm{CF})\int_{\mathrm{sunrise}}^{\mathrm{sunset}} I_b(\theta)\, cos\theta dt+\int_{\mathrm{sunrise}}^{\mathrm{sunset}} I_d(\theta)dt \tag{131d}$$

In this work, the integral was simply converted to summation and added up every 15 min to obtain total daily global radiation.

The cloud factor (CF) varies from zero for clear sky to 1 for overcast sky. This parameter could be obtained by use of the numbers of cloudy days in each month and the cloud cover. Cloud cover is observed every three hours in three different ranges: (0–2) octas, (3–6) octas, and (7–8) octas. To convert the cloud cover to cloud factor (CF), the following relationship is used [73]:

$$CF=\frac{(n_1)+4.5(n_2)+7.5(n_3)}{8(n_1+n_2+n_3)} \tag{131e}$$

where n_1, n_2 and n_3 are the total number of days in each month, with zero to 2/8, 3/8 to 6/8, and 7/8 to 8/8 octas, respectively.

2.2.3. Model 3: Daneshyar model

Following Paltridge and Proctor's [72] work, Daneshyar proposed his method by defining new coefficients for diffuse radiation adjusted for the climate conditions of Tehran, Iran [74]:

The hourly beam and diffuse radiation is calculated from following equations:

$$I_b=3.42286[1-exp(-0.075(90-\theta))] \tag{132a}$$

$$I_d=0.00515+0.00758(90-\theta)+0.43677\mathrm{CF} \tag{132b}$$

The mean monthly total radiation in (MJ/m^2 day) estimated, using time steps of 15 min, is:

$$H=(1-\mathrm{CF})\int_{\mathrm{sunrise}}^{\mathrm{sunset}} I_b(\theta)cos\theta dt+\int_{\mathrm{sunrise}}^{\mathrm{sunset}} I_d(\theta)dt \tag{132c}$$

2.2.4. Model 4: Badescu model

Badescu proposed the following correlations [75]:

$$\frac{H}{H_0}=a+bC \tag{133a}$$

$$\frac{H}{H_0}=a+bC+cC^2 \tag{133b}$$

$$\frac{H}{H_0}=a+bC+cC^2+dC^3 \tag{133c}$$

2.2.5. Model 5: Modified Daneshyar model (Sabziparvar model)

Sabziparvar [76] in 2007 made the following modifications to the Daneshyar method [74]:

(1) In Daneshyar method, solar constant of 1353 (W/m^2) has been used by the workers. Since the new suggested average value of solar constant is about 1367 (W/m^2) [77], the total daily global radiation was multiplied by a factor.
(2) For each month, the monthly mean global radiation was modified by the Sun–Earth distance correction factor.
(3) Height effect was also applied separately on beam and diffuse radiation. For calculation of the height correction factor in the new method, Tehran (where Daneshyar calibrated his suggested model) is taken as the reference. Details of this method are described in [76].

2.2.6. Model 6: Modified Paltridge model (Sabziparvar model)

Similar to method 5, Sabziparvar [76] in 2007 made the same modifications to the Paltridge–Proctor method [72]. For locations where sunshine duration are not observed, prediction by modified Paltridge model which only requires cloud data (are available easily by satellites and ground-based measurements) can be a good alternative. Details of this method are described in [76].

2.3. Temperature-based models

Cloud observations and sunshine data are not readily available in all of the locations. Therefore, developing some precise solar radiation models which use commonly available measured parameters such as air temperature is necessary. Due to the common availability of daily maximum and minimum air temperatures, several empirical methods have been proposed to estimate solar radiation from these variables, especially for locations where the air daily temperature is the only available meteorological data. The temperature based models assume 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 factors other than solar radiation that can influence the temperature difference such as cloudiness, humidity, latitude, elevation, topography, or proximity to a large body of water [78]. In the following section, the radiation models which use the maximum and minimum air temperatures are presented and classified based on their years of appearance.

2.3.1. Model 1: Hargreaves model

Hargreaves and Samani recommended a simple equation to estimate solar radiation using only maximum and minimum temperatures [79]:

$$\frac{H}{H_0}=a(T_{\max}-T_{\min})^{0.5} \tag{134}$$

Initially, coefficient a was set to 0.17 for arid and semi-arid regions. Hargreaves [80] later recommended using a=0.16 for interior regions and a=0.19 for coastal regions. One of the implications of this model for estimating daily global solar radiation is:

– Bayat and Mirlatifi model for Shiraz, Iran [81]:

$$\frac{H}{H_0}=0.16(T_{\max}-T_{\min})^{0.5} \tag{135}$$

2.3.2. Model 2: Bristow and Campbell model

Bristow and Campbell developed a simple model for daily global solar radiation with a different structure in which H is an exponential function of ΔT [82]:

$$\frac{H}{H_0}=a\left[1-exp\left(-b\Delta T^{c}\right)\right] \tag{136}$$

where ΔT is the temperature term difference. Although coefficients a, b and c are empirical, they have some physical meaning. Coefficient a represents the maximum radiation that can be expected on a clear day. Coefficients b and c control the rate at which a is approached as the temperature difference increases.

2.3.3. Model 3: Allen model

Following the work of Hargreaves and Samani [79] Allen in 1997 suggested employing a self-calibrating model to estimate mean monthly global solar radiation [78]:

$$\frac{H}{H_0}=K_r(T_{\max}-T_{\min})^{0.5} \tag{137}$$

Previously, Allen [83] had expressed the empirical coefficient (K_r) as a function of the ratio of atmospheric pressure at the site (P_S, kPa) and at sea level (P_0, 101.3 kPa) as follows:

$$k_r=k_{ra}\left(\frac{P_S}{P_0}\right)^{0.5} \tag{138}$$

For the empirical coefficient k_{ra}, Allen suggested values of 0.17 for interior regions and 0.20 for coastal regions. Allen reported that Eq. (138) performs poorly for sites having an elevation of more than 1500 m.

2.3.4. Model 4: Donatelli and Campbell model

Donatelli and Campbell algorithm is similar in structure to the Bristow and Campbell model [82], except taking into account two corrective functions of mean and minimum air temperature. The model has the following forms [84]:

$$(a)\quad \frac{H}{H_0}=a\left[1-exp\left(-bf(T_{avg})\Delta T^{2}f(T_{\min})\right)\right] \tag{139a}$$

$$T_{avg}=\frac{(T_{\max}+T_{\min})}{2} \tag{139b}$$

$$f(T_{avg})=0.017exp(exp(-0.053T_{avg})) \tag{139c}$$

$$f(T_{\min})=exp(T_{\min}/c) \tag{139d}$$

$$(b)\quad \frac{H}{H_0}=a\left[1-exp\left(-b\frac{\Delta T^{c}}{\Delta T_m}\right)\right] \tag{140}$$

where ΔT_m is monthly mean ΔT(°C)

$$(c)\quad \frac{H}{H_0}=a\left[1-exp(-bf(T_{avg})\Delta T^{c})\right] \tag{141a}$$

$$f(T_{avg})=0.017exp(exp(-0.053T_{avg}\Delta T^{c})) \tag{141b}$$

2.3.5. Model 5: Hunt et al. model

Hunt et al. [85] proposed following model by adding another coefficient (b) to Hargreaves and Samani model [79].

$$H=a(T_{\max}-T_{\min})^{0.5}H_0+b \tag{142}$$

2.3.6. Model 6: Goodin et al. model

Goodin et al. refined the Bristow and Campbell model [82] by adding an H_0-term meant to act as a scaling factor allowing ΔT to accommodate a greater range of H values [86]:

$$\frac{H}{H_0}=a\left[1-exp\left(-b\left(\frac{\Delta T^{C}}{H_0}\right)\right)\right] \tag{143}$$

The results proved that this model provides reasonably accurate estimates of irradiance at non-instrumented sites and that the model can successfully be used at sites away from the calibration site [87].

2.3.7. Model 7: Thorton and Running model

The method proposed by Thorton and Running is based on the Bristow and Campbell [82] study and is as follows [88]:

$$\frac{H}{H_0}=\tau_{t,\max}\tau_{f,\max} \tag{144}$$

where $\tau_{t,\max}$ is the maximum (cloud-free) daily total transmittance at a location with a given elevation and depends on the near-surface water-vapor pressure on a given day of the year, and $\tau_{f,\max}$ stands for the proportion of $\tau_{t,\max}$ observed on a given day (cloud correction).

2.3.8. Model 8: Meza and Varas model

Meza and Varas assumed that a and c coefficients of Bristow–Campbell [82] model are fixed and the only b coefficient was adjusted to minimize the square errors [89]:

$$\frac{H}{H_0}=0.75\left[1-exp\left(-b\Delta T^{2}\right)\right] \tag{145}$$

2.3.9. Model 9: Winslow model

The method proposed by Winslow et al. was designated as a globally applicable model and the prediction equation is [90]:

$$\frac{H}{H_0} = \tau Dl\left[1 - a\frac{e_s(T_{\min})}{e_s(T_{\max})}\right] \tag{146}$$

where $e_s(T_{\min})$ and $e_s(T_{\max})$ are saturation vapor pressures at min and max temperature, respectively. Variable τ accounts for atmospheric transmittance and is estimated from site latitude, elevation and mean annual temperature. Function Dl corrects the effect of site differences in day length, which causes a variation between the time of maximum temperature (and minimum humidity) and sunset [91].

The day-length correction (Dl) is approximated by:

$$Dl = \left[1 - H_{day} - \frac{(\pi/4)^2}{2H_{day}^{\ 2}}\right] - 1 \tag{147}$$

2.3.10. Model 10: Weiss et al. model

Weiss et al. simplified the Donatelli and Campbell [84] and Goodin [86] models which only needs one parameter (b) to be calibrated, while other coefficients (a and c) were fixed as $a=0.75$ and $c=2$ [92]:

$$(a) \quad \frac{H}{H_0} = 0.75\left[1 - exp\left(-bf(T_{avg})\Delta T^2\right)\right] \tag{148a}$$

$$f(T_{avg}) = 0.017exp\left(exp\left(-0.053T_{avg}\Delta T^2\right)\right) \tag{148b}$$

$$(b) \quad \frac{H}{H_0} = 0.75\left[1 - exp\left(-b\frac{\Delta T^2}{H_0}\right)\right] \tag{149}$$

2.3.11. Model 11: Annandale model

Annandale et al. modified Hargreaves and Samani [79] model by introducing a correction factor for parameter a to account the effects of reduced altitude and atmospheric thickness on H as [93]:

$$\frac{H}{H_0} = a\left(1 + 2.7 \times 10^{-5}Z\right)(T_{\max} - T_{\min})^{0.5} \tag{150}$$

where Z is the elevation above sea level in m.

Bayat and Mirlatifi used this model with $a=0.15$ to estimate the daily global solar radiation in Shiraz, Iran [81]:

$$\frac{H}{H_0} = 0.15\left(1 + 2.7 \times 10^{-5}Z\right)(T_{\max} - T_{\min})^{0.5} \tag{151}$$

2.3.12. Model 12: Mahmood and Hubbard model

Mahmood and Hubbard estimated daily solar radiation based on maximum and minimum daily air temperatures and proposed the following model [94]:

$$H = a(T_{\max} - T_{\min})^{0.69} H_0^{\ 0.91} \tag{152a}$$

$$H_{\text{mod}} = \frac{H - 2.4999}{0.8023} \tag{152b}$$

where H_{mod} is estimated solar radiation corrected for systematic bias, in MJ/m^2 day.

2.3.13. Model 13: Chen et al. model

Chen et al. presented the following models [95]:

$$\frac{H}{H_0} = a(T_{\max} - T_{\min})^{0.5} + b \tag{153a}$$

$$\frac{H}{H_0} = a\ ln(T_{\max} - T_{\min}) + b \tag{153b}$$

2.3.14. Model 14: Abraha and Savage model

Abraha and Savage fixed $a=0.75$ and $c=2$ in Donatelli and Campbell [84] model and proposed the following correlation [96]:

$$\frac{H}{H_0} = 0.75\left[1 - exp\left(-b\frac{\Delta T^2}{\Delta T_m}\right)\right] \tag{154}$$

2.3.15. Model 15: Abraha and Savage, Weiss et al. model

Weiss et al. and Abraha and Savage put $a=0.75$ in Donatelli and Campbell model [84] and reported the following relationship [92,96]:

$$\frac{H}{H_0} = 0.75\left[1 - exp\left(-bf(T_{avg})\Delta T^2 f(T_{\min})\right)\right] \tag{155}$$

2.3.16. Model 16: Almorox et al. model

A new method is proposed by Almorox et al. for estimating daily global solar irradiance in the form of [87]:

$$\frac{H}{H_0} = a(T_{\max} - T_{\min})^b\left[1 - exp\left(-c(e_s(T_{\min})/e_s(T_{\max}))^d\right)\right] \tag{156}$$

where $e_s(T_{\min})$ and $e_s(T_{\max})$ are saturation vapor pressures at minimum and maximum temperature, respectively. Saturation vapor pressure is related to air temperature and the relationship is expressed by [97]:

$$e_s(T) = 0.6108exp[17.27(T)/(T + 273.3)] \tag{157}$$

2.4. Other meteorological parameters-based models

Accurate prediction of the actual value of solar radiation for a given location requires long-term average meteorological data which are still scarce especially for underdeveloped and developing countries. Therefore it is not always possible to predict the solar irradiance for a particular location of interest. Many researchers have tried to use various available meteorological parameters such as precipitation, relative humidity, dew point temperature, soil temperature, evaporation and pressure alongside with the classical estimators such as sunshine, air temperature and cloudiness to predict the amount of global solar radiation. In the following section, the correlations which use the various meteorological variables are reported and classified based on their developing year.

2.4.1. Model 1: Swartman and Ogunlade model

Swartman and Ogunlade stated that the global radiation can be expressed as a function of the (S/S_0) ratio and mean relative humidity (RH) [98]:

$$H = a\left(\frac{S}{S_0}\right)^b RH^c \tag{158a}$$

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) + c\ RH \tag{158b}$$

2.4.2. Model 2: Sabbagh model

Sabbagh proposed following equation to estimate the monthly average daily global radiation that might be applicable to dry arid and semi-arid regions [99]:

$$H = 0.06407(K_g)exp\left[L\left(\frac{S}{12} - \frac{RH^{0.333}}{100} - \frac{1}{T_{\max}}\right)\right] \tag{159}$$

where K_g is geographical and seasonal factor and can be calculated from the following equation:

$$K_g = 100\left(\frac{0.2}{1+0.1L}S_0 + \psi_m cosL\right) \quad (160)$$

where ψ_m is a seasonal factor in month that is suggested by Reddy in [100].

The model is only reliable for locations with an average mean sea level of about 300 m and needs to be modified for arid regions with higher altitudes [99].

2.4.3. Model 3: Gariepy's model

Gariepy has reported that the empirical coefficients a and b in the Angström–Prescott [4] model are dependent on mean air temperature (T, °C) and the amount of mean precipitation (P, cm) [101]:

$$a = 0.3791 - 0.0041\,T - 0.0176\,P \quad (161a)$$

$$b = 0.4810 + 0.0043\,T + 0.0097\,P \quad (161b)$$

2.4.4. Model 4: Garg and Garg model

Garg and Garg proposed a double linear relation for obtaining monthly mean daily global solar radiation as follows [102]:

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) + cw \quad (162a)$$

where w(cm) is the atmospheric precipitable water vapor per unit volume of air and is computed according to Leckner [103]:

$$w = 0.0049RH\left[\frac{exp(26.23 - 5416/T_K)}{T_K}\right] \quad (162b)$$

– El-Metwally model for Egypt [7]

$$\frac{H}{H_0} = 0.219 + 0.526\left(\frac{S}{S_0}\right) + 0.004\,w \quad (163)$$

2.4.5. Model 5: Lewis model

Lewis reported that global solar radiation on a horizontal surface can be calculated by the following equations [104]:

$$H = aRH^b; \quad logH = a + b\,logRH \quad (164a)$$

$$H = aS^bRH^c; \quad logH = a + b\,logS + c\,logRH \quad (164b)$$

$$H = a\,exp(bS); \quad ln\,H = a + bS \quad (164c)$$

$$H = a\,exp(bRH); \quad ln\,H = a + bRH \quad (164d)$$

$$H = a\,expb(S - RH); \quad ln\,H = a + b(S - RH) \quad (164e)$$

2.4.6. Model 6: Ojosu and Komolafe model

Ojosu and Komolafe proposed the following equation [105]:

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) + c\left(\frac{T_{min}}{T_{max}}\right) + d\left(\frac{RH}{RH_{max}}\right) \quad (165)$$

2.4.7. Model 7: Gopinathan model

Gopinathan introduced a multiple linear regression equation of the form [49]:

$$\frac{H}{H_0} = a + bcos\varphi + cZ + d\left(\frac{S}{S_0}\right) + eT + fRH \quad (166)$$

2.4.8. Model 8: De Jong and Stewart model

De Jong and Stewart introduced the effect of precipitation in a multiplicative form as follow [106]:

$$\frac{H}{H_0} = a(T_{max} - T_{min})^b\left(1 + cP + dP^2\right) \quad (167)$$

where P is precipitation in mm.

2.4.9. Model 9: Abdalla model

Abdalla modified the Gopinathan [49] model for Bahrain as [107]:

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) + cT + dRH \quad (168a)$$

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) + cT + dRH + ePS \quad (168b)$$

Maghrabi [108] estimated the ability of this model for estimating monthly mean global solar radiation in kW h/m^2 for Tabouk, Saudi Arabia:

$$\frac{H}{H_0} = -0.107 + 0.70\left(\frac{S}{S_0}\right) - 0.0025T + 0.004RH \quad (169)$$

2.4.10. Model 10: Ododo et al. model

Ododo et al. proposed two new models as follow [109]:

$$\frac{H}{H_0} = a\left(\frac{S}{S_0}\right)^b T_{max}{}^c RH^d \quad (170a)$$

$$\frac{H}{H_0} = e + f\left(\frac{S}{S_0}\right) + gT_{max} + hRH + iT_{max}\left(\frac{S}{S_0}\right) \quad (170b)$$

2.4.11. Model 11: Hunt et al. model

Hunt et al. introduced precipitation (P, mm) and (T_{max}, °C) in an additive form that have had the highest accuracy at eight sites in Canada [85]:

$$H = a(T_{max} - T_{min})^{0.5}H_0 + bT_{max} + cP + dP^2 + e \quad (171)$$

2.4.12. Model 12: Supit and Van Kappel model

Supit and Van Kappel proposed a simple method to estimate daily global radiation and tested it for various locations in Europe, ranging from Finland to Italy [70].

$$H = H_0[a\sqrt{(T_{max} - T_{min})} + b\sqrt{(1 - C/8)}] + c \quad (172)$$

– Supit and Van Kappel model for London weather station, U.K. [70]

$$H = H_0[0.061\sqrt{(T_{max} - T_{min})} + 0.477\sqrt{(1 - C/8)}] - 0.557 \quad (173)$$

The regression coefficients of proposed method for various locations in Europe are presented in [70].

2.4.13. Model 13: Togrul and Onat model

Togrul and Onat investigated the effect of geographical, meteorological and astronomical parameters on the monthly mean global solar radiation and gave the following correlations [110]:

$$H = a + b\ \ sin\delta \quad (174a)$$

$$H = a + bH_0 \quad (174b)$$

$$H = a + bH_0 + c\left(\frac{S}{S_0}\right) \quad (174c)$$

$$H=a+b\left(\frac{S}{S_0}\right)+c\ sin\delta \tag{174d}$$

$$H=a+b\left(\frac{S}{S_0}\right)+c\ sin\delta+dT \tag{174e}$$

$$H=a+bH_0+c\left(\frac{S}{S_0}\right)+dST \tag{174f}$$

$$H=a+bH_0+c\left(\frac{S}{S_0}\right)+dRH+eST \tag{174g}$$

$$H=a+b\ \ sin\delta+c\left(\frac{S}{S_0}\right)+dRH+eT \tag{174h}$$

$$H=a+bH_0+c\left(\frac{S}{S_0}\right)+d\ sin\delta+eRH+fT \tag{174i}$$

$$H=a+bH_0+c\left(\frac{S}{S_0}\right)+dRH+eST+fT \tag{174j}$$

$$H=a+bH_0+c\left(\frac{S}{S_0}\right)+d\ sin\delta+eRH+fST+gT \tag{174k}$$

- Togrul and Onat model for Elazig, Turkey [110]

$$H=4.0891+6.459\ sin\delta \tag{175a}$$

$$H=-1.32+0.6757H_0 \tag{175b}$$

$$H=-1.3876+0.518H_0+2.3064\left(\frac{S}{S_0}\right) \tag{175c}$$

$$H=2.765+2.2984\left(\frac{S}{S_0}\right)+4.9597\ sin\delta \tag{175d}$$

$$H=2.6484+2.034\left(\frac{S}{S_0}\right)+5.2184\ sin\delta-0.0246T \tag{175e}$$

$$H=-1.489+0.528H_0+2.537\left(\frac{S}{S_0}\right)-0.0067ST \tag{175f}$$

$$H=-0.1764+0.523H_0+2.031\left(\frac{S}{S_0}\right)-0.0146RH-0.0162ST \tag{175g}$$

$$H=3.895+5.116\sin\delta+2.44\left(\frac{S}{S_0}\right)-0.0143RH-0.032T \tag{175h}$$

$$H=5.25-0.169H_0+2.5017\left(\frac{S}{S_0}\right)+6.525\ sin\delta-0.0144RH-0.034T \tag{175i}$$

$$H=-0.632+0.516H_0+2.3255\left(\frac{S}{S_0}\right)-0.0103RH+0.0373ST-0.062T \tag{175j}$$

$$H=4.591-0.1135H_0+2.522\left(\frac{S}{S_0}\right)+6.1589\ sin\delta-0.0124RH+0.0187ST-0.052T \tag{175k}$$

2.4.14. Model 14: Ertekin and Yaldiz model

Ertekin and Yaldiz estimated the monthly average daily global radiation by some multiple linear regression models using nine different variables: extra terrestrial radiation, solar declination, mean relative humidity, ratio of sunshine duration, mean temperature, mean soil temperature, mean cloudiness, mean precipitation (cm) and mean evaporation (cm) [2]:

$$H=a+b\delta \tag{176a}$$

$$H=a+bH_0+cT \tag{176b}$$

$$H=a+bH_0+c\left(\frac{S}{S_0}\right)+dC \tag{176c}$$

$$H=a+bH_0+cRH+d\left(\frac{S}{S_0}\right)+eC \tag{176d}$$

$$H=a+bH_0+cRH+d\left(\frac{S}{S_0}\right)+eT+fC \tag{176e}$$

$$H=a+bH_0+cRH+d\left(\frac{S}{S_0}\right)+eT+fC+iE \tag{176f}$$

$$H=a+bH_0+c\delta+dRH+e\left(\frac{S}{S_0}\right)+fST+gC+hE \tag{176g}$$

$$H=a+bH_0+c\delta+dRH+e\left(\frac{S}{S_0}\right)+fT+gST+hC+iE \tag{176h}$$

$$H=a+bH_0+c\delta+dRH+e\left(\frac{S}{S_0}\right)+fT+gST+hC+iP+jE \tag{176i}$$

- Ertekin and Yaldiz model for Antalya, Turkey [2]

$$H=13.58+0.333\delta \tag{177a}$$

$$H=-4.46+0.477H_0+0.226T \tag{177b}$$

$$H=-2.54+0.491H_0+4.99\left(\frac{S}{S_0}\right)-0.406C \tag{177c}$$

$$H=-6.158+0.487H_0+0.0772RH+4.508\left(\frac{S}{S_0}\right)-0.633C \tag{177d}$$

$$H=-7.248+0.506H_0+0.113RH+5.987\left(\frac{S}{S_0}\right)-0.075T-0.9204C \tag{177e}$$

$$H=-16.16+0.493H_0+0.219RH+9.282\left(\frac{S}{S_0}\right)-0.247T-0.831C+0.2273E \tag{177f}$$

$$H=-11.90+0.353H_0+0.109\delta+0.229RH+11.095\left(\frac{S}{S_0}\right)-0.279ST-0.995C+0.241E \tag{177g}$$

$$H=-12.57+0.361H_0+0.0997\delta+0.234RH+11.19\left(\frac{S}{S_0}\right)-0.069T-0.227ST-0.99C+0.251E \tag{177h}$$

$$H=-13.08+0.386H_0+0.0902+0.2254RH+11.59\left(\frac{S}{S_0}\right)-0.034T+0.251ST-0.977C-0.0072P+0.2373E \tag{177i}$$

Menges et al. calibrated Eq. (176i) for Konya, Turkey and obtained the empirical coefficients of this model as follow [111]:

$$H=20.296019-0.096134H_0+0.317593\delta-0.146422RH+10.705159\left(\frac{S}{S_0}\right)-0.288332T+0.021331ST+0.359791C+0.207588P-0.076444E \tag{178}$$

2.4.15. Model 15: Trabea and Shaltout model

Trabea and Shaltout introduced the following correlation to calculate the daily global solar radiation at five stations in Egypt [112]:

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) + cT_{\max} + dV + eRH + fPS \tag{179}$$

– Trabea and Shaltout model for Egypt [112]

$$\frac{H}{H_0} = -0.139 + 0.229\left(\frac{S}{S_0}\right) + 0.009T_{\max} + 0.004\ V + 0.002RH + 0.002PS \tag{180}$$

2.4.16. Model 16: El-Metwally model

El-Metwally proposed following simple new methods to estimate global solar radiation based on meteorological data over six stations in Egypt [113]:

$$H = aH_0 + bT_{\max} + cT_{\min} + dC + e \tag{181a}$$

$$H = aH_0 + bT_{\max} + cT_{\min} + dC \tag{181b}$$

$$H = exp(aH_0 + bT_{\max} + cT_{\min} + dC + e) \tag{181c}$$

2.4.17. Model 17: Chen et al. model

Chen et al. suggested a logarithmic relationship between the daily global solar radiation, daily extraterrestrial solar radiation and the temperature difference between the maximum and minimum daily air temperature as follow [95]:

$$\frac{H}{H_0} = a\ ln(T_{\max} - T_{\min}) + b\left(\frac{S}{S_0}\right)^c + d \tag{182}$$

2.4.18. Model 18: Modified Sabbagh method (Sabziparvar model)

Sabziparvar in 2007 revised Sabbagh [99] model to predict the monthly average daily solar radiation on horizontal surfaces in various cities in central arid deserts of Iran. The modification was made by the inclusion of following factors to Sabbagh model:

(1) Height correction factor, (2) Sun–Earth distance correction factor and (3) inclusion of monthly total number of dusty days [76].

2.4.19. Model 19: Bulut and Büyükalaca model

Bulut and Büyükalaca proposed a simple model for estimating the daily global radiation on a horizontal surface. The model is based on a trigonometric function, which has only one independent parameter, namely the day of the year [114]:

$$I = b + (a - b)\left|sin\left[\frac{\pi}{365}(n+5)\right]\right|^{1.5} \tag{183}$$

They examined their model for 68 provinces of Turkey [114].

Some investigator employed this model to estimate global solar radiation in different locations as follows:

– Bulut and Büyükalaca model for Ankara, Turkey [114]

$$I = 3.86 + (22.71 - 3.86)\left|sin\left[\frac{\pi}{365}(n+5)\right]\right|^{1.5} \tag{184}$$

– El-Sebaii et al. model For Jeddah, Saudi Arabia [19]

$$I = 14.92 + 9.61\left|sin\left[\frac{\pi}{365}(n+5)\right]\right|^{1.5} \tag{185}$$

2.4.20. Model 20: El-Sebaii et al. model

El-Sebaii et al. developed and presented empirical correlations between the monthly average of daily global solar radiation fraction (H/H_0) and various meteorological parameters [19]:

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) + cT \tag{186a}$$

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) + cRH \tag{186b}$$

$$\frac{H}{H_0} = a + bT + cRH \tag{186c}$$

$$\frac{H}{H_0} = a + b(T_{\max} - T_{\min}) + cC \tag{186d}$$

$$\frac{H}{H_0} = a + b(T_{\max} - T_{\min})^{0.5} + cC \tag{186e}$$

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) + cC \tag{186f}$$

– El-Sebaii et al. model For Jeddah, Saudi Arabia [19]

$$\frac{H}{H_0} = -1.92 + 2.60\left(\frac{S}{S_0}\right) + 0.006T \tag{187a}$$

$$\frac{H}{H_0} = -1.62 + 2.24\left(\frac{S}{S_0}\right) + 0.332RH \tag{187b}$$

$$\frac{H}{H_0} = 0.139 - 0.003T + 0.896RH \tag{187c}$$

$$\frac{H}{H_0} = 0.214 + 0.035(T_{\max} - T_{\min}) - 0.028C \tag{187d}$$

$$\frac{H}{H_0} = -0.08 + 0.21(T_{\max} - T_{\min})^{0.5} - 0.012C \tag{187e}$$

$$\frac{H}{H_0} = -2.76 + 3.72\left(\frac{S}{S_0}\right) + 0.001C \tag{187f}$$

2.4.21. Model 21: Maghrabi model

Maghrabi established a simple model to calculate the monthly mean global solar radiation on a horizontal surface using five meteorological parameters [108]:

$$H = a + b\left(\frac{S}{S_0}\right) + cT + dP_0 + e\ PWV + fRH \tag{188}$$

The precipitable water vapor (*PWV*) is calculated using the Reitan [115] equation as follows:

$$ln\ PWV\ (mm) = 0.1102 + 0.0613\ t_d \tag{189}$$

– Maghrabi model for Tabouk, Saudi Arabia [108]

$$H(\text{kW h/m}^2) = 163.01 - 1.04\left(\frac{S}{S_0}\right) + 0.12T - 0.21P_0 - 1.06PWV - 0.03RH \tag{190}$$

3. A case study

3.1. Experimental data

It is already mentioned that the main objective of this study is to comprehensively collect and review the global solar radiation models available in the literature and categorize them based on the employed meteorological parameters. In order to evaluate the applicability and accuracy of the collected models for computing the monthly average daily global solar radiation on a horizontal surface, the geographical and meteorological data of Yazd, Iran was used. Yazd city is located in latitude 31°54′N, longitude 54°17′E and its altitude of sea level is 1237.2 m. Yazd province is situated in the central part of Iranian plateau and because of being in the sun-belt, it is an ideal location to benefit the advantages of solar energy utilization and adoption of its related technologies [116]. The total radiation received by a horizontal surface in Yazd City during a year is reported to be around 7787 MJ/m^2 with about 3270 sunshine hours in a year while the number of overcast days is fewer than 1110 h per year [117]. In the present work, the value of measured data of daily global solar radiation on a horizontal surface in Yazd city in the period of 1982–2008, as well as number of sunshine hours, maximum, minimum and daily ambient temperatures, amount of cloud cover, relative humidity and the other related meteorological parameters during the period of 1988–2008 were obtained from the Islamic Republic of Iran Meteorological Office (IRIMO) data centre.

The measured global solar radiation data were checked and controlled for errors and inconsistencies. The purpose of data quality control was to eliminate faulty data and inaccurate measurements. After the quality control, the measured data were averaged to obtain the monthly mean daily values by taking the data for the average day of each month as recommended by Duffie and Beckman [118]. The measured data were then divided into two sets. The first sub-data set (1988–2003) were employed to develop empirical correlations between the monthly average daily global solar radiation fraction (H/H_0) and monthly average of desired meteorological parameters (for the global solar radiation this subset is contained the measured data of 1982–2003). The second sub-data set (2004–2008) were then used to validate and evaluate the derived models and correlations. The measured long-term monthly average daily global radiation distribution for Yazd city in the periods of 1982–2008 is shown in Fig. 1.

3.2. Statistical evaluation

The accuracy and performance of the derived correlations in predicting of global solar radiation was evaluated on the basis of the following statistical error tests which are coefficient of determination (R^2), root mean square error ($RMSE$), mean bias error (MBE), mean absolute bias error ($MABE$), mean percentage error (MPE), correlation coefficient (r) and t-Test statistic. These error indices are defined as:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (H_{i,m} - H_{i,c})^2}{\sum_{i=1}^{n} (H_{i,m} - \overline{H_m})^2} \tag{191}$$

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^{n} (H_{i,c} - H_{i,m})^2 \right]^{1/2} \tag{192}$$

$$MBE = \frac{1}{n} \sum_{i=1}^{n} (H_{i,c} - H_{i,m}) \tag{193}$$

$$MABE = \frac{1}{n} \sum_{i=1}^{n} |(H_{i,c} - H_{i,m})| \tag{194}$$

$$MPE(\%) = \frac{1}{n} \sum_{i=1}^{n} \left(\frac{H_{i,c} - H_{i,m}}{H_{i,m}} \right) \times 100 \tag{195}$$

$$r = \frac{\sum_{i=1}^{n} (H_{i,c} - \overline{H_c})(H_{i,m} - \overline{H_m})}{[\sum_{i=1}^{n} (H_{i,c} - \overline{H_c})^2 \sum_{i=1}^{n} (H_{i,m} - \overline{H_m})^2]^{1/2}} \tag{196}$$

In the above relations, the subscript i refers to the ith value of the solar irradiation and n is the number of the solar irradiation data. The subscripts "c" and "m" refer to the calculated and measured global solar irradiation values, respectively. $\overline{H_c}$ is the mean calculated global radiation and $\overline{H_m}$ is the mean measured global radiation.

Although these statistical indicators generally provide reasonable criteria to compare models, but do not objectively indicate whether the estimates from a model are statistically significant. The t-statistic (Eq. (197)) allows models to be compared and at the same time indicates whether a model's estimate is statistically significant at a particular confidence level or not.

$$t = \left[\frac{(n-1)(MBE)^2}{(RMSE)^2 - (MBE)^2} \right]^{1/2} \tag{197}$$

The smaller the t-*value*, the better the model performance is. To determine whether the estimates from a model are statistically significant, one simply has to determine from the standard statistical tables, the critical t-*value*, i.e., $(t_{\alpha/2})$ at α level of significance and $(n-1)°$ of freedom. The model is judged to be statistically significant if the calculated t-*value* is less than the critical value.

3.3. Result and discussion

3.3.1. Calibration

Linear, multiple linear and nonlinear regressions were carried out between the monthly mean measured global solar radiation and the meteorological parameters using the first sub-data set to obtain the values of empirical coefficients of the selected models from each category. The coefficient of determination (R^2) index is used to determine that how well the regression line approximates the real data points. A model is more efficient when R^2 is closer to 1. In addition, the t-*value* index is used to determine whether the estimates from a model are statistically significant or not. For the model's estimates to be judged statistically significant at the $(1-\alpha)$ confidence level, the calculated t-*value* must be less than the critical value. Regression coefficients of the selected models in each category for Yazd city along with the values of coefficients of determination (R^2) and t-*values* are presented in Table 1. It should be mentioned that several radiation models from each category is used for estimating the monthly average daily global solar radiation fraction (H/H_0), however, the results of one selected model from each category is presented in Table 1 for brevity.

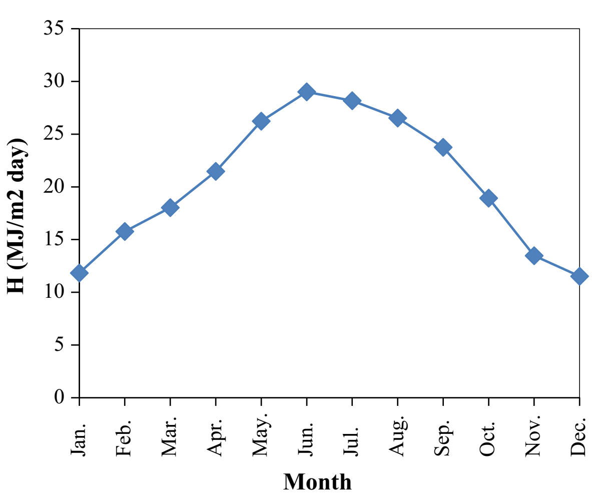

Fig. 1. The measured values of monthly average daily global solar radiation for Yazd city in the periods of 1982–2008.

Table 1
Regression coefficients of selected radiation models for Yazd city along with the values of coefficients of determination (R^2) and *t-value*.

Models	(R^2)	*t-value*	*a*	*b*	*c*	*d*
Sunshine-based models						
El-Metwally model (Eq. (116))	0.979	0.5234	0.7272			
Cloud-based models						
Badescu model (Eq. (133a))	0.9948	0.2663	0.7658	−0.0594		
Temperature-based models						
Hargreaves model (Eq. (134))	0.9543	0.2625	0.1746			
Other meteorological parameters-based models						
Chen et al. model (Eq. (182))	0.9971	0.3782	−0.01088	5.127	0.101	−4.299

Table 2
Statistical results for the validation of the selected models for Yazd city (using data in the period of 2004–2008).

Models	*RMSE* (MJ/m² day)	*MBE* (MJ/m² day)	*MABE* (MJ/m² day)	*MPE* (%)	*r*
Sunshine-based models					
El-Metwally model	0.5385	0.04371	0.4124	0.8485	0.9969
Cloud-based models					
Badescu model (a)	1.152	−0.3385	0.9592	−1.877	0.9846
Temperature-based models					
Hargreaves model	0.7103	−0.02285	0.6293	0.3039	0.9934
Other meteorological parameters-based models					
Chen et al. model	0.8542	0.2104	0.746	0.9859	0.9913

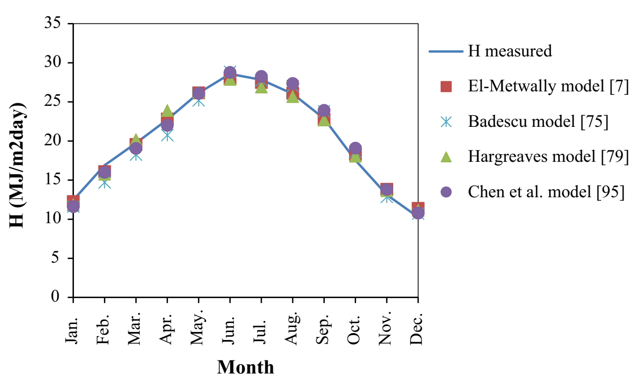

Fig. 2. Measured (in the periods of 2004–2008) and calculated values of monthly average daily global solar radiation for Yazd city.

The results of Table 1 show that all the selected models give the coefficients of determination (R^2) higher than 95%, indicating a very good fitting between the monthly average daily global radiation and the other meteorological parameters. The best fit is obtained by employing Chen et al. model [95]. Comparison between the different models according to the *t-value* shows that the calculated *t-values* are less than the critical *t-value* (2.201 at 95% confidence level), indicating that all models have statistical significance.

3.3.2. Validation

The performance of developed correlations in predicting the global solar radiation on horizontal surface is also assessed by comparing each models outputs and the measured values from the second subset data based on the *r*, *RMSE*, *MBE*, *MABE* and *MPE* error indices. A summary of all the statistical parameters are presented in Table 2. For higher modeling accuracy *RMSE*, *MBE*, *MABE* and *MPE* indices should be closer to zero, but correlation coefficient (*r*) should approach to 1 as closely as possible.

The performance of the most accurate models in each category for estimating the monthly average daily global solar radiation in Yazd is presented and compared in Table 2. From the statistical analysis, it can be seen that the estimated values of monthly mean daily global solar irradiation are in good agreement with the measured values for all models. It is found that the values of RMSE are in the range from 0.5385 to 1.152 (in MJ/m² day). The MBE achieved in this study for all models are in the acceptable range. Negative values of *MBE* in temperature and cloud based models indicate an underestimation of measured global solar radiation by these models. As an over-estimation of an individual observation may cancel under-estimation in a separate observation, using *MABE* index is more appropriate than *MBE*. The biggest value of *MABE* is belonged to Badescu model (a) with 0.9592. The mean percentage errors (*MPE*) of all models are in the range of acceptable values between 0.3039% and −1.877%. Also according to the statistical test of the correlation coefficient (*r*), all models give very good results (above 0.98). El-Metwally sunshine based model [7] gives the highest value of *r* with value of 0.9969, indicating a strong positive linear relationship between the measured and calculated values of the global solar radiation.

The measured values of the monthly average daily global radiation and corresponding calculated values by employing El-Metwally model [7], Badescu model [75], Hargreaves model [79] as well as Chen et al. model [95] for Yazd city are illustrated in Fig. 2. As may be seen, agreement between the values obtained from the selected models and the measured data are very good.

Based on the statistical indicators presented in Table 1 as well as Fig. 2, all models show good estimation of the monthly average daily global solar radiation on a horizontal surface for Yazd city. But the El-Metwally sunshine based model [7] produces the best result among the correlations developed in this study. Therefore, this model is recommended for the prediction of global solar radiation on a horizontal surface in Yazd and elsewhere with similar climatic conditions, where the radiation data are missing or unavailable.

The agreement between measured and calculated value of *H* was also confirmed for each month by calculating the relative percentage error (*e*). The relative percentage error for each month is defined as:

$$e = \left(\frac{H_{i,c} - H_{i,m}}{H_{i,m}} \right) \times 100 \tag{198}$$

Fig. 3 shows the comparisons of the relative percentage error (*e*) of measured and calculated *H* for all developed models. It is seen from Fig. 3 that the relative percentage error for each month rarely exceeds ±10%.

It is found from Fig. 3 that almost all methods provide low performance at both winter and spring, this is due to the increase of cloudiness and aerosol content, respectively.

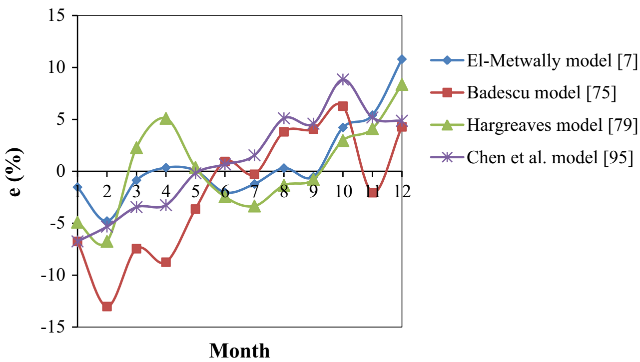

Fig. 3. Comparisons of monthly relative percentage error (e) of monthly average daily measured and calculated global solar radiation for Yazd (2004–2008).

4. Concluding remarks

Solar energy technologies offer opportunities for use of a clean, renewable, and domestic energy resource, and are essential components of a sustainable energy future. Availability of a complete and accurate solar radiation data base for each specific region is essential in the prediction, study, and design of solar energy systems. Information on global solar radiation at any sites (preferably obtained over a long period of time) is useful not only to the locality where the radiation data is collected but also for the wider world community.

A global study of the world distribution of global solar radiation requires knowledge of the radiation data in various countries. For the purpose of worldwide marketing, the designers and manufactures of solar equipment will need to know the average global solar radiation available in different regions. In this regard, a common practice is to estimate average daily global solar radiation using appropriate correlations which are empirically established by using the measured data at some selected locations. These correlations estimate the values of global solar radiation from more readily available meteorological, climatological, and geographical parameters. The number of such correlations or empirical equations that have been developed and tested is relatively high, which makes it difficult to choose the most appropriate correlation for a particular purpose and site.

In this study, a comprehensive collection and review of available solar models is conducted to assist in the selection of most appropriate and accurate model based on the available measured meteorological data. Moreover, the collected models are classified into four categories namely, sunshine-based, cloud-based, temperature-based, and other meteorological parameter-based models. The regression constants of some collected solar models have been generally presented to calculate the global solar radiation with high accuracy in a given location. These regression coefficients have been computed using measured monthly mean daily global radiation and other meteorological variables for locations of interest. The regression coefficients in the presented models differ from location to location. This may be due to the local and seasonal changes in the type and thickness of cloud cover, the effects of snow covered surfaces, the concentrations of pollutants, and latitude [13].

The correlations reported in this study have had the best estimation in the location of interest and the present classification of solar models make it easy to choose a suitable model from various existing models based on the meteorological parameters measured in the location of interest. These correlations with these selected variables can be used by solar energy system designers in the design and performance prediction of solar applications with fairly high level of accuracy in calibration sites and possibly in regions with similar climatic conditions.

Furthermore, to evaluate the accuracy and applicability of collected various models for estimating the monthly average daily global radiation on a horizontal surface, the long term measured meteorological and solar data of Yazd city, Iran is employed. With employing linear and nonlinear least square method, regression coefficients of some selected models from the four categories were obtained by using first sub-data set. The developed models were then compared with each other and with the experimental data of second subset on the basis of the statistical error indicators such as *RMSE*, *MBE*, *MABE*, *MPE* and correlation coefficient (r). The most accurate models in each category are then identified and presented. These models have reasonable values of estimation errors. Based on the statistical results, El-Metwally sunshine-based model reproduce the measured monthly average daily global solar irradiation for Yazd city with the highest accuracy.

A common feature of almost all models collected in this paper is that they account for latitude, solar declination, elevation, day length and atmospheric transmissivity by including the extraterrestrial radiation (H_0) term in the model. Among the four categories of solar radiation models, the sunshine-based methods are generally more accurate but they are often limited by the lack of availability of sunshine records. Estimation of global solar radiation from the air temperature offers an important alternative in the absence of measured H or sunshine duration because of the wide availability of air temperature data. The main advantage of models in this category is the readily available data. Temperature-based models are a convenient tool for estimating solar radiation if the parameters can be calibrated for each specific location [87]. The temperature range (ΔT) is the main factor affecting accuracy of the temperature-based models. Larger (ΔT) generally results in a better predictive accuracy, meaning that the temperature-based models are more applicable in areas with larger temperature range. This implies that model calibration is particularly sensitive in humid regions where (ΔT) is generally small [119].

When sunshine duration data are not available, prediction by the method that only requires cloud data (are available easily by satellites and ground-based measurements) can be a good alternative. One drawback of these models is that they are sensible to human biasing [70].

The models presented in the last category, employ more than one meteorological parameter for predicting the global solar radiation. These models reported a good estimation of solar radiation, but they are limited because of using the various meteorological parameters as models inputs that are not readily available in most of the location of interest. Moreover, to prevent the error of measurement tools also increasing speed, the solar radiation should be estimated using the minimum measured input parameters.

References

[1] Katiyar AK, Pandey CK. Simple correlation for estimating the global solar radiation on horizontal surfaces in India. Energy 2010:1–6.
[2] Ertekin C, Yaldiz O. Estimation of monthly average daily global radiation on horizontal surface for Antalya, Turkey. Renewable Energy 1999;17:95–102.
[3] Angström A. Solar and terrestrial radiation. Quarterly Journal of Royal Meteorological Society 1924;50:121–5.
[4] Prescott JA. Evaporation from water surface in relation to solar radiation. Transactions of the Royal Society of Australia 1940;46:114–8.
[5] Duffie JA, Beckman WA. Solar engineering of thermal processes. New York: Wiley; 1991.
[6] Jain PC. Global irradiation estimation for Italian locations. Solar and Wind Technology 1986;3(4):323–8.
[7] El-Metwally M. Sunshine and global solar radiation estimation at different sites in Egypt. Journal of Atmospheric and Solar-Terrestrial Physics 2005;67:1331–42.
[8] Bakirci K. Correlations for estimation of daily global solar radiation with hours of bright sunshine in Turkey. Energy 2009;34:485–501.

[9] Alsaad MA. Characteristic distribution of global radiation for Amman, Jordan. Solar and Wind Technology 1990;7(2/3):261–6.
[10] Jain S, Jain PC. A comparison of the Angström-type correlations and the estimation of monthly average daily global irradiation. Solar Energy 1988;40(2):93–8.
[11] Lewis G. An empirical relation for estimating global irradiation for Tennessee. USA Energy Conversion and Management 1992;33(12):1097–9.
[12] Tiris M, Tiris C, Erdalli Y. Water heating systems by solar energy. Marmara Research Centre, Institute of Energy Systems and Environmental Research, NATO TU-COATING, Gebze, Kocaeli, Turkey; 1997 [in Turkish].
[13] Almorox J, Hontoria C. Global solar radiation estimation using sunshine duration in Spain. Energy Conversion and Management 2004;45:1529–35.
[14] Raja IA, Twidell JW. Distribution of global insolation over Pakistan. Solar Energy 1990;44:63–71.
[15] Raja IA, Twidell JW. Diurnal variation of global insolation over five locations in Pakistan. Solar Energy 1990;44:73–6.
[16] Li H, Maa W, Lian Y, Wang X, Zhao L. Global solar radiation estimation with sunshine duration in Tibet, China. Renewable Energy 2011;36:3141–5.
[17] Said R, Mansor M, Abuain T. Estimation of global and diffuse radiation at Tripoli. Renewable Energy 1998;14(1–4):221–7.
[18] Ulgen K, Ozbalta N. Measured and estimated global radiation on horizontal surface for Bornova, Izmir. XII. National Thermal Science and Technical Congress, Izmir, Turkey; 2000. p. 113–8 [in Turkish].
[19] El-Sebaii AA, Al-Ghamdi AA, Al-Hazmi FS, Faidah A. Estimation of global solar radiation on horizontal surfaces in Jeddah, Saudi Arabia. Energy Policy 2009;37:3645–9.
[20] Rensheng C, Shihua L, Ersi K, Jianping Y, Xibin J. Estimating daily global radiation using two types of revised models in China. Energy Conversion and Management 2006;47:865–78.
[21] Ahmad F, Ulfat I. Empirical models for the correlation of monthly average daily global solar radiation with hours of sunshine on a horizontal surface at Karachi, Pakistan. Turkish Journal of Physics 2004;28:301–7.
[22] Jin Z, Yezheng W, Gang Y. General formula for estimation of monthly average daily global solar radiation in China. Energy Conversion and Management 2005;46:257–68.
[23] Akpabio LE, Etuk SE. Relationship between global solar radiation and sunshine duration for Onne, Nigeria. Turkish Journal of Physics 2003;27: 161–167.
[24] Ulgen K, Hepbasli A. Solar radiation models. Part 2: Comparison and developing new models. Energy Sources 2004;26:521–30.
[25] Aras H, Balli O, Hepbasli A. Global solar radiation Potential. Part 1. Model Development. Energy Sources Part B: Economics, Planning and Policy 2006;1:303–15.
[26] Togrul IT, Togrul H. Global solar radiation over Turkey: comparison of predicted and measured data. Renew Energy 2002;25:55–67.
[27] Kholagi A, Ramadan MRI, Ali ZEH, Fattah YA. Global and diffuse solar irradiance in Yemen (Y.A.R). Solar Energy 1983;31(1):55–62.
[28] Jain PC. A model for diffuse and global irradiation on horizontal surface. Solar Energy 1990;45(5):301–8.
[29] Veeran PK, Kumar S. Analysis of monthly average daily global radiation and monthly average sunshine duration at two tropical locations. Renewable Energy 1993;3(8):935–9.
[30] Chegaar M, Chibani A. Global solar radiation estimation in Algeria. Energy Conversion and Management 2001;42:967–73.
[31] Ampratwum DB, Dorvlo ASS. Estimation of solar radiation from the number of sunshine hours. Applied Energy 1999;63:161–7.
[32] Glower J, McGulloch JSG. The empirical relation between solar radiation and hours of sunshine. Quarterly Journal of the Royal Meteorological Society 1958;84:172.
[33] Ulgen K, Hepbasli A. Comparison of solar radiation correlations for Izmir, Turkey. International Journal of Energy Research 2002;26:413–30.
[34] Page JK. The estimation of monthly mean values of daily total short wave radiation on vertical and inclined surfaces from sunshine records for latitudes 40°N–40°S. In: Proceedings of UN conference on new sources of energy; 1961 .p .378–90.
[35] Rietveld M. A new method for estimating the regression cofficients in the formula relating solar radiation to sunshine. Agricultural Meteorology 1978;19:243–52.
[36] Dogniaux R, Lemoine M. Classification of radiation sites in terms of different indices of atmospheric transparency. Solar energy research and development in the European Community, series F, vol. 2. Dordrecht, Holland: Reidel; 1983.
[37] Kilic A, Ozturk A. Solar energy. Istanbul: Kipas Yayincilik; 1983 [in Turkish].
[38] Benson RB, Paris MV, Sherry JE, Justus CG. Estimation of daily and monthly direct diffuse and global solar radiation from sunshine duration measurements. Solar Energy 1984;32(4):523–35.
[39] Ogelman H, Ecevit A, Tasdemiroglu E. A new method for estimating solar radiation from bright sunshine data. Solar Energy 1984;33:619–25.
[40] Akinoglu BG, Ecevit A. A further comparison and discussion of sunshine based models to estimate global solar radiation. Energy 1990;15:865–72.
[41] Tasdemiroglu E, Sever R. An improved correlation for estimating solar radiation from bright sunshine data for Turkey. Energy Conversion and Management 1991;31(6):599–600.
[42] Yildiz M, Oz S. Evaluation of the solar energy potential of Turkey. In: Proceedings of the sixth national energy congress; 1994. p. 250–260 [in Turkish].
[43] Aksoy B. Estimated monthly average global radiation for Turkey and its comparison with observations. Renewable Energy 1997;10:625–33.
[44] Tahran S, Sarı A. Model selection for global and diffuse radiation over the Central Black Sea (CBS) region of Turkey. Energy Conversion and Management 2005;46:605–13.
[45] Bahel V, Srinivasan R, Bakhsh H. Solar radiation for Dhahran, Saudi Arabia. Energy 1986;11:985–9.
[46] Zabara K. Estimation of the global solar radiation in Greece. Solar and Wind Technology 1986;3(4):267–72.
[47] Bahel V, Bakhsh H, Srinivasan R. A correlation for estimation of global solar radiation. Energy 1987;12:131–5.
[48] Gopinathan KK. A simple method for predicting global solar radiation on a horizontal surface. Solar and Wind Technology 1988;5:581–3.
[49] Gopinathan KK. A general formula for computing the coefficients of the correlations connecting global solar radiation to sunshine duration. Solar Energy 1988;41:499–502.
[50] Newland FJ. A study of solar radiation models for the coastal region of South China. Solar Energy 1988;31:227–35.
[51] Soler A. Monthly specific Rietveld's correlations. Solar and Wind Technology 1990;7:305–8.
[52] Luhanga PVC, Andringa J. Characteristic of solar radiation at Sebele, Gaborone, Botswana. Solar Energy 1990;44:71–81.
[53] Louche A, Notton G, Poggi P, Simonnot G. Correlations for direct normal and global horizontal irradiation on a French Mediterranean site. Solar Energy 1991;46:261–6.
[54] Samuel TDMA. Estimation of global radiation for Sri Lanka. Solar Energy 1991;47:333–7.
[55] Ertekin C, Yaldiz O. Comparison of some existing models for estimating global solar radiation for Antalya (Turkey). Energy Conversion and Management 2000;41:311–30.
[56] Bakirci K. Estimation of global solar radiation on horizontal surface. Journal of Thermal Science and Technology 2007;27(1):7–11 [in Turkish].
[57] Gopinathan KK, Soler A. A sunshine dependent global insolation model for latitudes between 60°N and 70°N. Renewable Energy 1992;2(4/5):401–4.
[58] Bennett I. Monthly maps of mean daily insolation for United States. Solar Energy 1965;9:145–59.
[59] Raja IA. Insolation sunshine relation with site elevation and latitude. Solar Energy 1994;53:53–6.
[60] Coppolino S. A new correlation between clearness index and relative sunshine. Renewable Energy 1994;4(4):417–23.
[61] Tiris M, Tiris C, Ture IE. Correlations of monthly-average daily global, diffuse and beam radiations with hours of bright sunshine in Gebze, Turkey. Energy Conversion and Management 1996;37:1417–21.
[62] Klabzuba J, Bures R, Koznarova V. Model calculation of daily sums of global radiation used in growth models. In: Proceedings of the bioclimatology labour hours, Zvolen; 1999. p. 121–2.
[63] Togrul IT, Togrul H, Evin D. Estimation of monthly global solar radiation from sunshine duration measurements in Elazig. Renewable Energy 2000;19:587–95.
[64] Elagib N, Mansell MG. New approaches for estimating global solar radiation across Sudan. Energy Conversion and Management 2000;41:419–34.
[65] Togrul IT, Togrul H, Evin D. Estimation of global solar radiation under clear sky radiation in Turkey. Renewable Energy 2000;21:271–87.
[66] Almorox J, Benito M, Hontoria C. Estimation of monthly Angström–Prescott equation coefficients from measured daily data in Toledo, Spain. Renewable Energy 2005;30:931–6.
[67] Sen Z. Simple nonlinear solar irradiation estimation model. Renewable Energy 2007;32:342–50.
[68] Bakirci K. Correlations for estimation of solar radiation on horizontal surface. Journal of Energy Engineering 2008;134(4):130–4.
[69] Muzathik AM, Ibrahim MZ, Samo KB, Wan Nik WB. Estimation of global solar irradiation on horizontal and inclined surfaces based on the horizontal measurements. Energy 2011;36:812–8.
[70] Supit I, Van Kappel RR. A simple method to estimate global radiation. Solar Energy 1998;63:147–60.
[71] Black JN. The distribution of solar radiation over the earth's surface. Archiv fur Meteorologie, Geophysik, und Bioklimatologie Serie A Meteorologie und Geophysik 1956;7:165–1889.
[72] Paltridge GW, Proctor D. Monthly mean solar radiation statistics for Australia. Solar Energy 1976;18(3):235–43.
[73] Samimi J. Estimation of height-dependent solar irradiation and application to the solar climate of Iran. Solar Energy 1994;52(5):401–9.
[74] Daneshyar M. Solar radiation statistics for Iran. Solar Energy 1978;21: 345–349.
[75] Badescu V. Correlations to estimate monthly mean daily solar global irradiation: application to Romania. Energy 1999;24:883–93.
[76] Sabziparvar AA. A simple formula for estimating global solar radiation in central arid deserts of Iran. Renewable Energy 2008;33:1002–10.
[77] Royal Meteorological Institute of Belgium. Department of aerology; 2004: 〈http://remotesensing.Oma.be/Radiometry_Papers〉.
[78] Allen R. Self-calibrating method for estimating solar radiation from air temperature. Journal of Hydrologic Engineering 1997;2:56–67.
[79] Hargreaves GH, Samani ZA. Estimating potential evapotranspiration. Journal of Irrigation and Drainage Engineering 1982;108(IR3):223–30.
[80] Hargreaves GH. Simplified coefficients for estimating monthly solar radiation in North America and Europe. Departmental paper, Departmental of Biological and Irrigation Engineering, Utah State University, Logan; 1994.

[81] Bayat K, Mirlatifi SM. Estimation of daily global solar radiation using regression models and artificial neural network. Agriculture's Science and Natural Resources Magazine 2009;16:3 [in Persian].
[82] Bristow KL, Campbell GS. On the relationship between incoming solar radiation and daily maximum and minimum temperature. Agricultural and Forest Meteorology 1984;31:59–166.
[83] Allen R. Evaluation of procedures of estimating mean monthly solar radiation from air temperature. Rome: FAO; 1995.
[84] Donatell M, Campbell GS. A simple model to estimate global solar radiation. In: Proceedings of the fifth European society of agronomy congress, Nitra, Slovak Republic; 1998. p. 133–4.
[85] Hunt LA, Kucharb L, Swanton CJ. Estimation of solar radiation for use in crop modeling. Agricultural and Forest Meteorology 1998;91:293–300.
[86] Goodin DG, Hutchinson JMS, Vanderlip RL, Knapp MC. Estimating solar irradiance for crop modeling using daily air temperature data. Agronomy Journal 1999;91:845–51.
[87] Almorox J, Hontoria C, Benito M. Models for obtaining daily global solar radiation with measured air temperature data in Madrid (Spain). Applied Energy 2011;88:1703–9.
[88] Thorton PE, Running SW. An improved algorithm for estimating incident daily solar radiation from measurements of temperature, humidity and precipitation. Agricultural and Forest Meteorology 1999;93:211–28.
[89] Meza F, Varas E. Estimation of mean monthly solar global radiation as a function of temperature. Agricultural and Forest Meteorology 2000;100: 231–241.
[90] Winslow JC, Hunt ER, Piper SC. A globally applicable model of daily solar irradiance estimated from air temperature and precipitation data. Ecological Modelling 2001;143:227–43.
[91] Trnka M, Zalud Z, Eitzinger J, Dubrovsky M. Global solar radiation in Central European lowlands estimated by various empirical formulae. Agricultural and Forest Meteorology 2005;131:54–76.
[92] Weiss A, Hays CJ, Hu Q, Easterling WE. Incorporating bias error in calculating solar irradiance: implications for crop yield simulations. Agronomy Journal 2001;93:1321–6.
[93] Annandale JG, Jovanic NZ, Benade N, Allen RG. Software for missing data error analysis of Penman–Monteith reference evapotranspiration. Irrigation Science 2002;21:57–67.
[94] Mahmood R, Hubbar KG. Effect of time of temperature observation and estimation of daily solar radiation for the Northern Great Plains, USA. Agronomy Journal 2002;94:723–33.
[95] Chen R, Ersi K, Yang J, Lu S, Zhao W. Validation of five global radiation models with measured daily data in China. Energy Conversion and Management 2004;45:1759–69.
[96] Abraha MG, Savage MJ. Comparison of estimates of daily solar radiation from air temperature range for application in crop simulations. Agricultural and Forest Meteorology 2008;148:401–16.
[97] Allen RG, Pereira LS, Raes D, Smith M. Crop evapotranspiration. Guidelines for computing crop water requirements. FAO irrigation and drainage paper 56, Rome; 1998.
[98] Swartman RK, Ogunlade O. Solar radiation estimates from common parameters. Solar Energy 1967;11:170–2.
[99] Sabbagh J, Sayigh AAM, EMA Al-Salam. Estimation of the total solar radiation from meteorological data. Solar Energy 1977;19:307–11.
[100] Reddy SJ. An empirical method for the estimation of total solar radiation. Solar Energy 1971;13:289–91.
[101] Gariepy J. Estimation of global solar radiation. International report, Service of meteorology, Government of Quebec, Canada; 1980.
[102] Garg HP, Garg ST. Prediction of global solar radiation from bright sunshine hours and other meteorological parameters. Solar-India, proceedings on national solar energy convention. New Delhi: Allied Publishers; 1982 p. 1.004–7.
[103] Leckner B. The spectral distribution of solar radiation at the earth's surface-elements of a model. Solar Energy 1978;20:143–50.
[104] Lewis G. Estimates of irradiance over Zimbabwe. Solar Energy 1983;31: 609–612.
[105] Ojosu JO, Komolafe LK. Models for estimating solar radiation availability in south western Nigeria. Nigerian Journal of Solar Energy 1987;6:69–77.
[106] De Jong R, Stewart DW. Estimating global solar radiation from common meteorological observations in western Canada. Canadian Journal of Plant Science 1993;73:509–18.
[107] Abdalla YAG. New correlation of global solar radiation with meteorological parameters for Bahrain. International Journal of Solar Energy 1994;16: 111–120.
[108] Maghrabi AH. Parameterization of a simple model to estimate monthly global solar radiation based on meteorological variables, and evaluation of existing solar radiation models for Tabouk, Saudi Arabia. Energy Conversion and Management 2009;50:2754–60.
[109] Ododo JC, Sulaiman AT, Aidan J, Yuguda MM, Ogbu FA. The importance of maximum air temperature in the parameterisation of solar radiation in Nigeria. Renewable Energy 1995;6:751–63.
[110] Togrul IT, Onat E. A study for estimating solar radiation in Elazig using geographical and meteorological data. Energy Conversion and Management 1999;40:1577–84.
[111] Menges HO, Ertekin C, Sonmete MH. Evaluation of global solar radiation models for Konya, Turkey. Energy Conversion and Management 2006;47: 3149–3173.
[112] Trabea AA, Shaltout MAM. Correlation of global solar radiation with meteorological parameters over Egypt. Renewable Energy 2000;21:297–308.
[113] El-Metwally M. Simple new methods to estimate global solar radiation based on meteorological data in Egypt. Atmospheric Research 2004;69:217–39.
[114] Bulut H, Büyükalaca O. Simple model for the generation of daily global solar radiation data in Turkey. Applied Energy 2007;84:477–91.
[115] Reitan CH. Surface dew point and water vapour aloft. Journal of Applied Meteorology 1963;2:776–9.
[116] Dehghan AA. Status and potentials of renewable energies in Yazd Province-Iran. Renewable and Sustainable Energy Reviews 2011;15:1491–6.
[117] Saffaripour MH, Mehrabian MA. Modeling of solar radiation and comparison with empirical data. Presented at the 16th annual international Iranian mechanical engineering conference (in Persian), Mechanical Engineering Dept., Shahid Bahonar University of Kerman, Iran; 2008.
[118] Duffie JA, Beckman WA. Solar engineering of thermal processes. 2nd ed. New York: Wiley; 1991.
[119] Liu X, Mei X, Li Y, Wang Q, Jensen JR, Zhang Y, Porter JR. Evaluation of temperature-based global solar radiation models in China. Agricultural and Forest Meteorology 2009;149:1433–46.