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# Total Global Solar Radiation Estimation Models and Applications: A review

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## ABSTRACT

In many developing countries, main parameters are measured at meteorological stations, but in some stations solar radiation measurements may not be available. Solar radiation measurements may not be performed due to equipment installation, maintenance, repair costs and calibration requirements. The best way to achieve a physical value is to measure. Estimation models are used to obtain solar radiation values where measurements are not exist. These models allow estimating global solar radiation with the aid of other measured meteorological parameters. In this study, a literature review is given, the global solar radiation estimation models and their applications are mentioned.

***Keywords:*** Global total solar radiation; estimation models; meteorological models; cloudiness; sunshine duration.

## 1. INTRODUCTION

Solar radiation is the main source of energy for the ecosystem, playing a key role in biophysical activities, energy sector, architectural design and similar activities. Solar radiation measurements are important for such activities. Solar radiation is the basic source of renewable energy in the environment, and this energy type has been studied since antiquity.

Studies on the prediction of solar radiation are based on very old studies. Isaac Newton examined the intensity of solar radiation by observing temperature changes that occur along with the effect of the sunshine on the earth. It has been known for many years that solar radiation has increased air temperatures. Years ago, experiments were carried out in this context. Investigations were made by examining the status of thermometers under solar radiation [1].

In many developing countries, main meteorological parameters are measured at meteorological stations. Rarely, solar radiation measurements cannot be applied due to equipment installation, maintenance, repair costs and calibration requirements in some stations. The best way to achieve a physical value is measuring. Estimation models are used to obtain solar radiation values where measurements are not available or not possible.

At stations where solar measurements are taken, it appears that there can be a lack of recorded solar radiation values. Solar radiation estimation models are mathematical expressions that can be used to close these deficiencies. These expressions generally give the empirical correlation between solar radiation and other meteorological parameters. The most related parameters in solar radiation prediction models are; sunshine time, maximum air temperature, minimum air temperature and cloudiness.

Based on the estimation of solar radiation, it has been observed in the literature that long-lasting studies have been conducted. Angstorm-Prescott model was founded by Angstorm [2] and developed by Prescott [3] at the beginning of the 20th century. This model has been studied by other researchers. Different mathematical models were presented by different researchers. These mathematical studies have revealed several estimation models that try to establish the relationship between different meteorological parameters and global solar radiation.

Models presented in the literature are mathematical expressions that have been worked on for certain regions. For example; Coppolino [4] has developed a model in Italy for solar radiation estimation and confirmed this work in certain regions of Italy. In the same way, Hargreaves [5] presented a model for Senegal. After these studies, other researchers used these models for different regions. They made publications about which model was suitable for the region where they were working. Empirical models should be calibrated for a certain region; the empirical coefficients used in calibration for a region may not be used directly for other regions. In this study, the models in the literature will be shared. As well as, the applications in the literature of these models for different regions will be given.

Increases in the cost of fossil fuels, unknowns in reserves, and increased environmental pollution make renewable energy important. Solar energy, wind energy and biomass stand out as renewable energy sources. The global solar radiation parameter is an important factor for the installation and operation of solar energy systems [6, 7].

The physical state of solar radiation in complex weather conditions can be examined as in Figure 1. Here, diffuse radiation scattered from small cloud clusters, aerosols, air particles and clouds. Weakening of direct radiation differs according to the layer thickness and number of clouds. The solar diffuse radiation consists of multiple scattering. They are scattering from air molecules, scattering from aerosols, scattering from particles, multiple reflections and diffuse radiation resulting from attenuation of clouds. Multiple reflected diffuse irradiation strongly depends on the reflection properties of the clouds, the positioning of the clouds. If the position of the clouds is irregular, diffuse irradiation is anisotropic. Diffuse radiation is usually isotropic if the sky has a layer covered with complex clouds. The sum of direct and diffuse radiation is called global radiation [8].

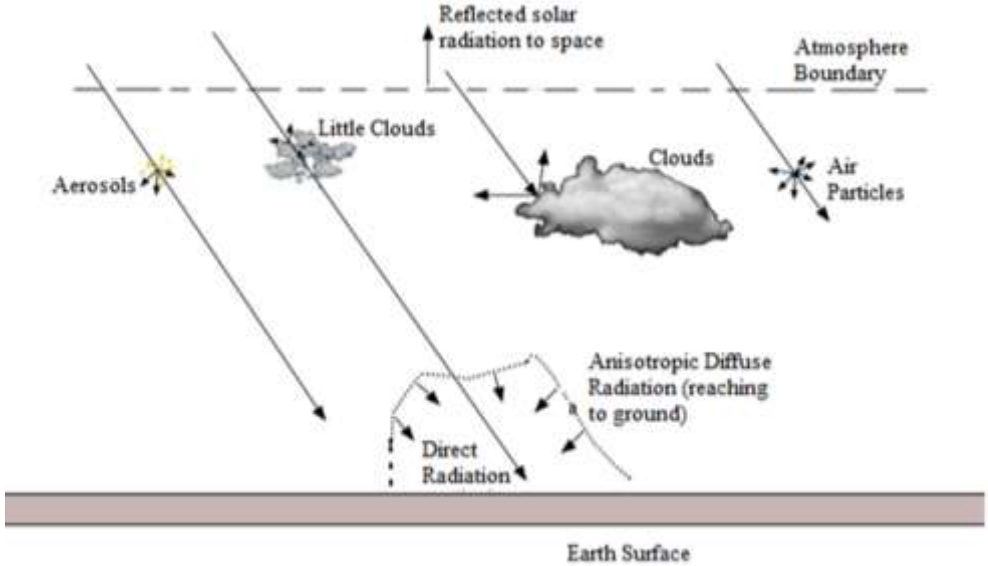


Figure 1. Solar radiation in complex weather conditions

## 2. STUDIES IN THE LITERATURE

First, it is useful to give basic equations before estimation models are given. These equations are frequently used in estimation models.

The spectral distribution of the radiation reaching the outside of the Earth's atmosphere layer is important for applications such as photovoltaic power systems of satellite systems. This information is also important for photochemical processes and the selection of suitable materials for spacecraft [8].

The solar constant represents the total solar energy of all the wavelengths falling in a square meter on Earth's orbit. Actually, this value is not a constant. Over the years it has only minor changes such as one-tenth of a percent. This constant is expressed with $I_{sc}$ (1367 W/m$^2$ = 4.92 MJ/day • m$^2$). This constant is used in many solar energy applications and solar radiation calculations. In the past, this value was expressed as NASA design solar constant of 1353 W/m$^2$. In many past solar radiation estimation models, this value is used as solar constant. The new value of solar constant is reported in the literature as 1367 W/m$^2$ [8].

An equation expresses the extraterrestrial radiation. This expression is used in global solar radiation estimation models. The theoretical mathematical expression of extraterrestrial radiation is seen in Equation 1. In this mathematical equation, extraterrestrial solar radiation is expressed as $H_0$ (MJ • m$^{-2}$ • day$^{-1}$), solar constant as $I_{sc}$ (4,921 MJ / day • m$^2$), eccentricity factor as $E_0$, latitude ø) and the solar angle as $\omega_s$ (in degrees) at sunrise [8]. Extraterrestrial radiation refers to the solar radiation falling on the first extraterrestrial surface. Extraterrestrial radiation is the intensity of the solar radiation at the top of the Earth's atmosphere.

$$H_0 = \frac{24}{\pi} \cdot I_{sc} \cdot E_0 \cdot sin(ø) \cdot sin(\delta) * [\left(\frac{\pi}{180}\right) \cdot \omega_s - tan(\omega_s)] \quad (1)$$

Eccentricity is the difference in shape between an ellipse and a perfect circle. The eccentricity factor, which represents the eccentricity of the world, is used in many engineering and basic technology applications. The expression in simplified form appears in Equation 2. Here, "$J$" refers to the day of the calendar [8].

$$E_0 = 1 + 0{,}033 \cdot cos(\frac{2\pi * J}{365}) \quad (2)$$

The mathematical expression of the sunrise angle is given in Equation 3 [8].

$$\omega_s = cos^{-1}[-tan(ø) \cdot tan(\delta)] \quad (3)$$

Regarding the solar declination angle, Equation 4 can be considered [9]. Solar declination is the angle between the sunrays and the plane of the earth.

$$sin\delta = 0{,}39785 * sin[278{,}97 + 0{,}9856J + 1{,}9165 * sin(356{,}6 + 0{,}9856J)] \quad (4)$$

There are many estimation models in the literature, developed by various researchers are shared in this chapter. In solar estimation models, letters in alphabetical order (such as a, b…) represent empirical coefficients.

**Angstrom-Prescott model:** Sunshine duration is commonly used a parameter in the estimation of global solar radiation [10]. Angstrom-Prescott model provides a linear relationship between sunshine duration and solar radiation. The model is given in Equation 5 [2, 3]. S0 is the maximum possible sunshine duration; it can be calculated as in Equation 6 [11]. In this section, basic mathematical expressions used in solar radiation models will be given.

$$\frac{H}{H_0} = a + b\frac{S}{S_0} \tag{5}$$

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

**Almorox-Hontoria model:** Almorox-Hontoria is available in literature. This model is given in Equation 7. The model was calibrated for Spain [12].

$$\frac{H}{H_0} = a + b * \exp(\frac{S}{S_0}) \tag{7}$$

**Ampratwum-Dorvlo model:** The Ampratwum-Dorvlo model is given in Equation 8. The model was built by calibrating for Oman [13].

$$\frac{H}{H_0} = a + b * \log(\frac{S}{S_0}) \tag{8}$$

**Coppolino model:** The model proposed by Coppolino in the literature for the duration of sunshine is given in Equation 9. The model was calibrated around Italy [4].

$$\frac{H}{H_0} = e^a(\frac{S}{S_0})^b \tag{9}$$

**Hay model:** Hay interpreted Angstrom's equation from a different point of view. Hay model is seen in Equation 10 [14].

$$\frac{H\prime}{H_0} = a + b\frac{S}{S_0} \tag{10}$$

*H*’ value is obtained from Equation 11 [14, 15].

$$H - H' = H\rho[\rho_a\left(\frac{S}{S_0'}\right) + \rho_c\left(1 - \frac{S}{S_0'}\right)] \tag{11}$$

$\rho$ is the surface albedo, $\rho_a$is the surface albedo under clear skies, $\rho_c$ is the cloud albedo. $S_0'$ is expressed in Equation 12 [14, 15].

$$S_0' = 7.5\left(\frac{\arccos(cos85 - sinø \cdot sin\delta)}{cosø \cdot cos\delta}\right) \tag{12}$$

**McCulloch model:** McCulloch model incorporates the latitude effect as a parameter. The model is seen in Equation 13 [15, 16].

$$\frac{H}{H_0} = 0.29 \cdot cosø + 0.52\frac{S}{S_0} \tag{13}$$

**Rietveld model:** Rietveld has offered a model that is believed to be applied worldwide. This model is given in Equation 14 [17]. It can be said that this model expresses the worldwide applicable coefficients of the Angstrom-Prescott model.

$$\frac{H}{H_0} = 0.18 + 0.62\frac{S}{S_0} \tag{15}$$

**Gariepy model:** Gariepy has suggested mathematical expressions for a and b empirical coefficients of Angstorm-Prescott model depending on the amount of precipitation (P) and mean air temperature (T). These coefficients’ expressions are given in Equation 16 and 17 [18].

$$a = 0.3791 - 0.0041T - 0.0176P \tag{16}$$

$$b = 0.481 + 0.0043T + 0.0097P \tag{17}$$

**Zhao model:** Zhao has estimated the global solar radiation using sunshine duration and air pollution index (API). Linear, exponential and logarithmic models were presented in

Zhao's study. These models were applied in China, are given in Equation 18, 19 and 20 [19].

$$\frac{H}{H_0} = a + b\frac{S}{S_0} + c\frac{API}{100} + d\frac{S}{S_0}\frac{API}{100} \quad (18)$$

$$\frac{H}{H_0} = a + b\frac{S}{S_0} + c \cdot \exp(\frac{API}{100}) + d\frac{S}{S_0}\exp(\frac{API}{100}) \quad (19)$$

$$\frac{H}{H_0} = a + b\frac{S}{S_0} + c \cdot \log(\frac{API}{100}) + d\frac{S}{S_0}\log(\frac{API}{100}) \quad (20)$$

**Gopinathan model:** A linear regression has performed with data set for two locations in Lesotho (Lesotho and Roma). As the result of these applications, three correlations were derived. $H_d$ represents diffuse radiation on a horizontal surface. These correlations are given in Equation 21, 22 and 23 [20].

$$\frac{H}{H_0} = 0.406 + 3.043\frac{S}{S_0} \quad (21)$$

$$\frac{H_d}{H_0} = 0.260 - 1.312\frac{S}{S_0} \quad (22)$$

$$\frac{H_d}{H} = 0.550 - 3.819\frac{S}{S_0} \quad (23)$$

**Bakırcı model:** Bakırcı has given a correlation to estimate global solar radiation from sunshine duration in Turkey. The correlation is given in Equation 24 [21].

$$\frac{H}{H_0} = a + b\frac{S}{S_0} + c \cdot \exp(\frac{S}{S_0}) \quad (24)$$

**Samuel model:** Samuel has presented a cubic model. These model was used to estimate monthly mean daily global solar radiation from sunshine durations in Sri-Lanka (Equation 25) [22].

$$\frac{H}{H_0} = a + b\frac{S}{S_0} + c\left(\frac{S}{S_0}\right)^2 + d\left(\frac{S}{S_0}\right)^3 \quad (25)$$

**Ögelman model:** Ögelman's study gives a quadratic estimation correlation. These model uses sunshine duration as a parameter (Equation 26). These model has been applied to Ankara and Adana, Turkey [23].

$$\frac{H}{H_0} = a + b\frac{S}{S_0} + c\left(\frac{S}{S_0}\right)^2 \quad (26)$$

**Luis model:** Luis and others analyzed the relationship between global solar radiation and sunshine duration for Gran Canaria island (Spain) and gave an exponential relationship. This relationship is seen in Equation 27 [24].

$$\frac{H}{H_0} = a \cdot \exp(b\frac{S}{S_0}) \quad (27)$$

**Jamil-Siddiqui model:** Jamil and Siddiqui developed a model to estimate diffuse solar radiation on a horizontal surface. This model is related to global solar radiation and sunshine duration (Equation 28) [25].

$$\frac{H_d}{H} = a + b\frac{H}{H_0} + c\left(\frac{H}{H_0}\right)^2 + d\frac{S}{S_0} + e\left(\frac{S}{S_0}\right)^2 \quad (28)$$

**Newland model:** Newland developed a linear logarithmic model to give the correlation between global solar radiation and sunshine duration. This model is given in Equation 29 [26].

$$\frac{H}{H_0} = a + b\frac{S}{S_0} + c \cdot log\frac{S}{S_0} \quad (29)$$

**Badescu model:** Badescu model based on mean cloud cover data ($C$) is given in Equation 30, developed for Romania [27].

$$\frac{H}{H_0} = a + bC \qquad (30)$$

**Supit and Kapel model:** Supit and Kapel developed a model based on cloudiness and maximum ($T_{max}$), minimum ($T_{min}$) air temperatures. This model is seen in Equation 31 [28].

$$\frac{H}{H_0} = H_0\left[a\sqrt{(T_{max} - T_{min})} + b\sqrt{\left(1 - \frac{C}{8}\right)}\right] + c \qquad (31)$$

**Kasten and Czeplak model:** In literature, there is studies addressing the relationship between global total solar radiation and cloud cover. Kasten and Czeplak gave this relationship as in Equation 32 [29, 30].

$$\frac{H}{H_0} = 1.0 - aC^b \qquad (32)$$

**Luo model:** Luo and others developed a regression model from solar radiation observations at Lake Rotorua, New Zealand. Equation 33, gives polynomic cubic relation to estimate global solar radiation for Lake Rotorua region [30].

$$\frac{H}{H_0} = 1 - 1.9441C^3 + 2.8777C^2 - 2.2023C \qquad (33)$$

**Angstorm-Savinov model:** The relationship between mean cloudiness and the global solar radiation is given in Equation 34. There is a constant, named k, in the equation. This constant defines the transmission of solar radiation within the clouds and varies between 0.5 in high altitudes, 0,33 in low altitudes [31, 32, 33].

$$\frac{H}{H_0} = 1 - (1 - k)C \qquad (34)$$

**Sarkar model:** Sarkar presented the relationship between cloudiness and sunshine duration. This model is given in Equation 35 because it is useful for estimating the duration of sunshine [32].

$$\left(1 - \frac{S}{S_0}\right) = aC^2 + bC + c \qquad (35)$$

**Allen model:** Allen model is one of the models in the literature that relates the maximum ($T_{max}$) and minimum ($T_{min}$) air temperatures to global radiation, and is given in Equation 36 [14].

$$\frac{H}{H_0} = a * (T_{max} - T_{min})^{0,5} \qquad (36)$$

**Hargreaves model:** The Hargreaves model, which relates temperatures and global solar radiation, is given in Equation 37 [34].

$$\frac{H}{H_0} = a * (T_{max} - T_{min})^{0,5} + b \qquad (37)$$

**Chen model:** Chen model is given in Equation 38 [4].

$$\frac{H}{H_0} = a * ln(T_{max} - T_{min}) + b \qquad (38)$$

**Bristow-Campbell model:** Bristow-Campbell model was given as a study based on the difference between maximum and minimum temperatures (ΔT) [35].

$$\frac{H}{H_0} = a * [1 - \exp\{-b * (\Delta T)^c\}] \quad (39)$$

**De Jong and Stewart model:** De Jong and Stewart developed a model based on total precipitation (P) and the range in daily temperature extremes (ΔT). This model is given in Equation 40 [36].

$$\frac{H}{H_0} = a(\Delta T)^b[1 + cP + dP^2] \quad (40)$$

**Annandale model:** Annandale and others gave the altitude effect in their model. The model, that is based on altitude (z) and air temperature variations (ΔT) are given in Equation 41 [37].

$$\frac{H}{H_0} = a(1 + 2.7 \cdot 10^{-5} \cdot z)\sqrt{\Delta T} \quad (41)$$

**Hunt models:** Hunt and others developed solar radiation models. The model based on air temperature variations (ΔT) is given in Equation 42. Other model, which is related to precipitation (P) and maximum ($T_{max}$), minimum air temperatures($T_{min}$), is given in Equation 43 [38].

$$\frac{H}{H_0} = a\Delta T + \frac{b}{H_0} \quad (42)$$

$$\frac{H}{H_0} = a\Delta T + \frac{b \cdot T_{max}}{H_0} + \frac{c \cdot P}{H_0} + \frac{d \cdot P^2}{H_0} + \frac{e}{H_0} \quad (43)$$

**Goodin model:** Goodin and others gave the relationship between global solar radiation and air temperature variation. Goodin model is given in Equation 44 [39].

$$\frac{H}{H_0} = a * [1 - \exp\left\{-b * \frac{(\Delta T)^2}{H_0}\right\}] \quad (44)$$

**Meza and Varas model:** Meza and Varas developed a model similar as Bristow-Campbell model. The model is seen in Equation 45 [40].

$$\frac{H}{H_0} = 0.75 * [1 - \exp\{-b * (\Delta T)^2\}] \quad (45)$$

**Ajayi models:** Ajayi and others have developed five models to apply in Nigeria. These models are given in E quation 46, 47, 48, 49 and 50. In these models: ø = latitude (°), S = the daily sunshine hours, J = day number of the year, $S_0$ = maximum sunshine duration or day length, $T_{max}$ = maximum daily temperature (°C), n = day number in the year, RH = daily relative humidity, and a, b, c, d, e, f, g, h, i, j, k, l, m are correlation coefficients. H is the daily global solar irradiance value ($W/m^2$ ) [41].

$$H = a \cdot cos\o + b \cdot cosJ + c \cdot T_{max} + d\frac{S}{S_0} + e\frac{T_{max}}{RH} + f\left(\frac{T_{max}}{RH}\right)^2 + g \cdot cos\o . cosJ + h \quad (46)$$

$$H = a \cdot cos\o + b \cdot cosJ + c \cdot T_{max} + d\frac{S}{S_0} + e\frac{T_{max}}{RH} + f\left(\frac{T_{max}}{RH}\right)^4 + g \cdot cos\o . cosJ + h\frac{T_{max}}{cos\o} + i \quad (47)$$

$$H = a \cdot cos\o + b \cdot cosJ + c \cdot T_{max} + d\frac{S}{S_0} + e\frac{S}{S_0}^3 + f\frac{T_{max}}{RH} + g\left(\frac{T_{max}}{RH}\right)^2 + h\left(\frac{T_{max}}{RH}\right)^3 + i \cdot cos\o . cosJ + j\frac{T_{max}}{cos\o} + k \cdot cos^2 J + l \quad (48)$$

$$H = a \cdot cos\o + b \cdot cosJ + c \cdot T_{max} + d\frac{S}{S_0} + e\frac{S}{S_0}^3 + f\frac{T_{max}}{RH} + g\left(\frac{T_{max}}{RH}\right)^2 + h\left(\frac{T_{max}}{RH}\right)^3 + i\left(\frac{T_{max}}{RH}\right)^4 + j \cdot cos\o . cosJ + k\frac{T_{max}}{cos\o} + l \cdot cos^2 J + m \quad (49)$$

$$H = a \cdot cos\o + b \cdot cosJ + c \cdot T_{max} + d\frac{S}{S_0} + e\frac{T_{max}}{RH} + f \cdot RH + g \cdot cos\o . cosJ + h\frac{T_{max}}{cos\o} + i\left(\frac{T_{max}}{RH}\right)^2 + k \cdot cos^2 J + l \quad (50)$$

**Maghrabi model:** Magrabi carried out multiple regression between global solar radiation and meteorological parameters. These parameters are perceptible water (P), atmospheric pressure ($P_{atm}$), relative humidity (RH), air temperature (T), and sunshine hour (S). This model was applied to Tabrouk, Saudi Arabia, is given in Equation 51 [42].

$$H = 163.01 - 1.04\frac{S}{S_0} + 0.12T - 021P_{atm} - 1.06P - 0.03RH \quad (51)$$

**Alnaser model:** Alnaser have developed several models to estimate global solar radiation for Bahrein. These models were applied with Bahrein's meteorological data. The model, which have highest correlation coefficient is given in Equation 52. ST indicates solar temperature, RH is relative humidity, S is sunshine duration and T is air temperature[43].

$$H = -1213.996 + 0.5830H_0 - 249.419sin\delta - 9.713RH + 2634.331\frac{S}{S_0} - 33.606T + 16.961ST \quad (52)$$

**Kılıç and Öztürk model:** Kılıç and Öztürk gave mathematical relationships for a and b coefficients of Angstorm-Prescott model. These mathematical expressions are given in Equation 53 and 54. In these equations: z = altitude (m), δ = solar declination angle (°), ø = latitude (°) [44].

$$a = 0.103 + 0.000017z + 0.198\cos(\o - \delta) \quad (53)$$

$$b = 0.533 - 0.165\cos(\o - \delta) \quad (54)$$

**Swartman and Ogunlade model:** Swartman and Ogunlade have developed a solar radiation estimation model, that related to sunhine duration and relative humidity [45].

$$\frac{H}{H_0} = a\left[\frac{S}{S_0}\right]^b RH^c \quad (55)$$

**Yaniktepe model:** Yaniktepe and others suggested two equations to estimate global solar radiation. These equations are seen in E quation 56 and 57. S indicates sunshine hour, T is average air temperature [46].

$$\frac{H}{H_0} = a + b\left[\frac{S}{S_0}\right] + c \cdot T \quad (56)$$

$$\frac{H}{H_0} = a + b \cdot T \quad (57)$$

**Donatelli and Campbell model:** Donatelli and Campbell suggested the following mathematical expression (Equation 58) [47].

$$\frac{H}{H_0} = a * [1 - \exp\left\{-b * \left(\frac{\Delta T}{T_m}\right)^c\right\}] \quad (58)$$

**Liu model:** Liu and others improved the Angstorm model over Tibetan Plateau. In their study, mathematical expressions to calculate a and b empirical coefficients are given.

These expressions are seen in Equation 59 and 60. In these equations: z = altitude (m), $P_{vap}$ = average daily water vapor pressure (hPa) [48].

$$a + b = 0.106 \cdot \ln(z) - 0.060 \quad (59)$$

$$b = 0.373 \cdot \frac{1}{P_{vap}} + 0.483 \quad (60)$$

**Korachagaon-Bapat model:** Korachagaon and Bapat has developed a model that claims to estimate global solar radiation on earth's surface around the globe. This formula monthly averaged estimated global solar radiation (Equation 61). In this equation: z = altitude (m), ø = latitude (°), $T_{max}$ = Maximum monthly average air temperature (°C), $T_{min}$ = Minimum monthly average air temperature (°C) [49].

$$\frac{H}{H_0} = \frac{7.9}{ø} * \sqrt{(T_{max} - T_{min}) \cdot sinø \cdot \exp(-0.0001184 \cdot z)} \quad (61)$$

**Jakhrani model:** Jakhrani and other have developed a solar radiation estimation model. This model is given in Equation 62 [50].

$$\frac{H}{H_0} = a + \frac{T_{max}}{RH} S \quad (62)$$

**Adhikari model:** Adhikari and others have studied on estimation of global solar radiation for four selected sites in Nepal using sunshine hours, temperature and relative humidity. A new model was proposed in the study. This model is given in Equation 63. In this equation: $T_{av}$ = monthly average mean temperature in Kelvin, $T_{max}$ = monthly mean daily maximum temperature in Kelvin, RH = relative humidity [51].

$$\frac{H}{H_0} = a + b\frac{S}{S_0} + c\frac{T_{av}}{T_{max}} + d \cdot \ln(RH) \quad (63)$$

Liu and Scott studied on the estimation of solar radiation in Australia. In the study, different models for Australia were evaluated for estimating solar radiation. It has been said that solar radiation can be estimated using data from a meteorological station in a region with similar climate characteristics, if solar radiation data is not available. The study was based on the estimation of solar radiation using precipitation and temperature data in Australia. Meteorological data were collected from 39 stations in Australia. Models in the literature have been used in the study, and new equations have been proposed in Australia. These models are based on minimum temperature, precipitation and temperature. Three different models in the literature were calibrated for Australia, and error results were given for each station separately. The temperature-dependent Bristow-Campbell model was calibrated at meteorological stations in Australia and $R^2$ values were around 0.7 while at some stations values of 0.28, 0.44 were found. It is also seen that the RMSE values are around 2 to 3 MJ / $m^2$. It can be said that this situation is similar for models predicting only precipitation data (McCaskill model). It is thought that the model using both precipitation and temperature data is slightly better [52].

Almorox have applied 14 solar radiation estimation models in the literature to Aranjuez, Spain. These models depend on various meteorological parameters. A new equation for Aranjuez was developed based on saturation vapor pressure, precipitation amount and daily minimum relative humidity. Richardson-Reddy model, Annandale model and Goodman model's error results were seen satisfactory [53].

Toğrul, derived empirical coefficients for Angstrom model in Bishkek and compared the results obtained from the model with the measured values [54].

Spokas and Forcella have worked on the estimation of solar radiation with a limited number of meteorological data. In the model, latitude, longitude, altitude, daily precipitation, maximum and minimum temperatures are used as input parameters. 18

meteorological stations were identified as the study area. Since the meteorological stations in the study area have limited data, the model could not be confirmed with the measurement data. As verification method, other solar radiation estimation models in the literature have been used. It has been reported that the model developed in the study is compatible with the models in the literature [55].

Trnka and others worked on the estimation of solar radiation in low altitude areas of Central Europe. In Austria and Czech Republic, seven experimental equations in the literature have been applied [56].

Meza and Varas studied on the estimation of solar global radiation, using Bristow-Campbell and Allen models on monthly average meteorological data in Chile. In the study, the coefficients of the models for the 20 meteorological stations in Chile were derived [40].

Wong and Chow have applied some global solar radiation estimation models in the literature for Hong Kong and compared them using the difference between measured and estimated data [57].

Okonkwo and Nwokoye studied on global solar radiation estimation for Minna area in Niger. Solar radiation, maximum and minimum temperatures in this region were recorded between 2000 and 2012. The average daily solar radiation values per month were tried to be estimated using the ratios of the maximum and minimum temperatures. These parameters were regressed linearly, quadratically and cubically [58].

Bocco, Willington and Arias compared neural network models and regression equations for solar radiation. The meteorological data on the study were taken from Salta Station in Argentina between 1996 and 2002. Models created with artificial neural networks in the study were shown better performance [59].

Gana and Akpootu have applied Angstrom-type empirical correlation for estimating solar radiation in northeast Nigeria. Sunshine hour data (15-year data) were collected for Bauchi, Dutse, Ibitaraba, Maiduguri, Nguru and Yola. The Angstrom model was used when estimating the monthly mean solar radiation values, a and b coefficients of the model were derived using the equations in the literature with the help of latitude and sunshine hour. When the tables given in the study were examined, it is seen that the model gives errors up to 60%. The equations used when derived the coefficients for the Angstrom equation are seen in Equations 64 and 65 [60].

$$a = -0{,}110 + 0{,}235 * cos\text{ø} + 0{,}323\frac{S}{S_0} \tag{64}$$

$$b = 1{,}449 - 0{,}553 * cos\text{ø} - 0{,}694\frac{S}{S_0} \tag{65}$$

Yang, Huang and Tamai have developed a hybrid model for estimating global solar radiation. The model was used to calculate the monthly average daily radiation. The Angstorm model was rearranged using theoretical expressions. The study was applied to 14 meteorological stations in Japan [15].

Tymivios et al. studied on comparing Angstrom and artificial neural network methodologies. In the study, these methods used to estimate solar radiation in the horizontal plane in Cyprus. The Angstrom model coefficients were derived separately from the monthly average daily radiation and daily radiation values for Cyprus. In addition, different coefficients for each month were derived and three different coefficient derivation methods for Cyprus were tested for the Angstrom model. The Angstrom model has been shown better performance with coefficients derived separately for each month. One of the methods using artificial neural networks is given better results for Cyprus than Angstrom model [61].

Mubiru and Banda studied on the estimation of monthly average global solar radiation with artificial neural networks. The study was confirmed with the help of meteorological data recorded in Uganda. Sunshine hours, cloudiness, maximum temperature, latitude, longitude and altitude parameters were used as input parameters in the model [62].

Thornton and Running have studied on an algorithm for estimating solar radiation with measured temperature, humidity and precipitation data. In the study, data from 40 stations in the US were used [63].

Jin and others have studied on general formulization for estimating monthly mean daily solar radiation values in China. Data from 69 meteorological stations were used in modeling the solar radiation [64].

Sabziparvar has studied on the estimation of solar radiation in the arid deserts of Iran. The reason for this work is that solar radiation measurement systems in the desert are not common. Three different solar radiation estimation models in the literature have been revised to estimate the average daily solar radiation for different cities in the Iranian desert [65].

Elagib and Mansell have examined sunshine periods for estimating solar radiation in Sudan. In the study, the data of the meteorological stations in Sudan were used, the Angstrom coefficients were emphasized [66].

Myers has studied on the quality of solar radiation measurement systems and solar radiation models for renewable energy applications. It has been noted that models can only be verified with data obtained from calibrated devices that have traceability [67].

Jiang has studied on estimation of monthly average daily diffuse solar radiation in China. The study was examined for eight meteorological stations in China. It is noted in the study, quadratic equations perform better on diffuse solar radiation estimation [68].

Trabea and Shaltout have studied on the correlation of global solar radiation in Egypt. Input parameters of the correlation are maximum temperature, relative humidity, pressure at sea level, vapor pressure and sunshine duration. A solar radiation estimation model that can be used within the Egyptian borders has been proposed [69].

Nguyen and Pryor have examined the relationship between global solar radiation and sunshine durations in Vietnam. Monthly mean daily global radiation and sunshine duration values were obtained from meteorological stations in Vietnam. Angstrom equation was applied to Vietnam [70].

Podesta et al. have worked on the estimation of solar radiation in Pampas, Argentina. In the study, two scenarios were discussed. One of these scenarios is that sunshine duration data exists, and the other scenario is that only daily temperature data is available [71].

Ülgen and Hepbaşlı studied on diffuse solar radiation estimation models for the big cities of Turkey. The study was examined for Ankara, İstanbul and İzmir, and the models in the literature were used to estimate diffuse radiation in these cities [72].

Nijmeh and Mamlook have tested two models to calculate global solar radiation in Oman Jordan. These are Liu-Jordan's isotropic model and Hay's anisotropic model. Models are compared with RMSE and MBE error analysis methods. It is reported that the isotropic model yielded better results in the summer months, while the anisotropic model gave better results in the remainder of the year [73].

Iziomon and Mayer have tested cloud-based and sunshine duration based solar radiation estimation models in the literature with data from meteorological stations in Germany [74].

## 3. RESULTS AND DISCUSSION

Solar radiation can be theoretically and physically modeled under the conditions of cloudless and clear sky. Estimation models used in cloudy weather conditions generally depend on cloudiness, temperature and sunshine duration. These models was shared in the study. Models given in the literature have been calibrated by different researchers for several regions. Solar estimation model applications for different regions have been mentioned within the scope of this study. Solar radiation estimation models are produced for the regions studied. Generally, the model used must be calibrated before being used in each different region. Thus, empirical coefficients will be derived and regional usage of the models will be provided.

Solar radiation is expressed in the literature by regression and correlation of different meteorological parameters.

Solar radiation estimates have been studied for many years and are still being studied. Estimation models are mathematical equations using measured parameters. With the development of measurement systems, more accurate measurements can be made and as a result of more accurate measurements, more precise models can be developed.

## 4. CONCLUSION

Global solar radiation is an important parameter that have to be known for engineering calculations, renewable energy applications, agriculture and architectural designs. There are cases where this value can not be measured or does not exist in meteorological stations. In this case, empirical solar radiation estimation models are used to obtain these data. Among these models, Angstorm model based on cloudiness, Bristow-Campbell model, Chen model, Allen model and Hargreaves model, which depend on daily temperature variations, are the foreground. There are many applications in the literature regarding these models.

## CONFLICT OF INTERESTS

The authors would like to confirm that there is no conflict of interests associated with this publication and there is no financial fund for this work that can affect the research outcomes.

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